Erasmus University Rotterdam
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MSc Urban, Port and Transport Economics

CARBON CAPTURE AND STORAGE (CCS) AN ASSESSMENT OF THE BARRIERS AND UNCERTAINTIES FOR THE FULL-SCALE DEPLOYMENT

Master Thesis

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Abstract

Carbon Capture and Storage (CCS) is nowadays considered to be a crucial technology regarding the carbon abatement strategies in order to tackle irreversible climate change. Although demonstration of full scale integrated CCS systems in various locations globally is already taking place, there are still significant technical, economic, political and financial barriers and uncertainties about CCS. A great challenge for the stakeholders is that the number of barriers and uncertainties for the full scale deployment of CCS is too high. The aim of this thesis therefore, is to identify the barriers and uncertainties related to the full scale deployment of CCS, present how do different stakeholders assess the barriers and how these barriers and uncertainties identified can be overcome. The methodology chosen for the assessment of the barriers and uncertainties is the Multi-Criteria Assessment (MCA), in which three scenarios are created, a short-term, a medium-term and a long-term, against which the barriers and uncertainties will be assessed. Eight experts from the governmental, scientific, business and environmental sector were interviewed, which although small, still an indicative sample. This thesis results in that the most important barriers and uncertainties for the full scale deployment of CCS are the economic and financial viability, the insufficient CO_2 price, the need for stronger incentive mechanisms, the public acceptance, the lack of robust-transparent legal framework and the renewable energy competition. The process of interviewing experts also interestingly revealed that apart from the barriers identified in the literature review from existing social science literature, there are additional barriers to consider and assess for the deployment of CCS in further research. The additional barriers are the political urgency of climate change, the willingness to pay more for our energy supplies, the lack of infrastructure, the efficiency in CO_2 capturing process, the unawareness of the climate change by the public, the lack of a global framework and the differences in views between different stakeholders. The assessment process by the experts interviewed reveals that there are significant differences between different stakeholders on how they perceive and score the barriers for the full scale deployment of CCS. The most significant differences are met in carbon lock-in and dependency on fossil fuel. Regarding on how to overcome the barriers and uncertainties for the full-scale deployment of CCS, the political willingness, the collaboration between governments, business sector, scientists and society and the awareness of climate change are met to be crucial.

Preface

The right balance between economic development, environmental protection and quality of urban living was the motivation of this thesis. The finalizing of this thesis means the end of my Master studies in Urban, Port and Transport Economics, Rotterdam Erasmus University, the Netherlands. The entire procedure of the thesis was a great lesson itself to be taught.

I would like to thank my thesis supervisor Dr. Bart Kuipers and co-reader of my thesis Prof. dr. Harry Geerlings for their meetings, guidance, motivation, useful insights and critical points into my topic during the procedure.

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A special thanks goes to my parents and sister for their precious support, most importantly support in my decisions.

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Charalampos Chouliaras
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List of abbreviations

ACCSEPT	Acceptance of CO_2 Capture, Storage, Economics, Policy and Technology
CBA	Cost-Benefit Analysis
CC	Carbon Capture
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
DTI	Department of Trade and Industry
ECN	Energy Centre Netherlands
ECX	European Climate Exchange
EIA	Environmental Investigation Agency
EOR	Enhanced Oil Recovery
ETS	Emissions Trading Scheme
EU	European Union
EUA	European Union Allowance
EUROFER	European Steel Association
GHG	Green House Gas
IEA	International Energy Agency
kWh	Kilowatt-hour
LCA	Life –Cycle Assessment
MADA	Multi-Attribute Decision Analysis
MCA	Multi-Criteria Analysis

MCM	Multi-Criteria Mapping
NUMBY	Not Under My Back Yard
OTA	Office of Technology Assessment
RE	Renewable Energy
RCI	Rotterdam Climate Initiative
RES	Renewable Energy Sources
RD%D	Research Development& Demonstration
TA	Technology Assessment
UNFCCC	United Nations Framework Convention on Climate Change
USDOE	United States Department Of Energy
ZEP	Zero Emission Platform

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Outline of the thesis

This thesis contains eight chapters with subparagraphs. Chapter one is the introduction of the thesis. In Chapter two the research questions that this thesis aims at answering are presented. In Chapter three the research approach is described. Chapter four presents the methodology used. Chapter five presents the literature review. Chapter six contains the results of the research. Chapter seven presents the discussion. Finally, Chapter eight presents the conclusions that this research resulted in.

CHAPTER 1

INTRODUCTION

1.1 Background

Our society is heavily dependent on fossil fuels, which supply about 81% of the world's primary energy (International Energy Agency, 2011). Fossil fuels are used to produce about 67% of the world's electricity, to which coal, natural gas and oil contribute about 41%, 21% and 5%, respectively (Sathre, Chester, Cain, & Masanet, 2012). The growing global demand for energy services, as well as the relative abundance of fossil fuels and the proven technologies for using them, suggest that fossil fuels will continue to be widely used in the future. This raises concern of climate destabilization caused by increasing atmospheric concentration of carbon dioxide CO_2 released during the combustion of fossil fuels (Intergovernmental Panel on Climate Change, 2011).

Technologies are being developed to capture a part of the CO_2 released by fuel combustion and industrial processes and to sequester the CO_2 in long-term storage sites (Sathre, Chester, Cain, Masanet, 2012). Carbon Capture and Storage (CCS) is nowadays often considered to be a crucial technology in the long term carbon abatement strategies of many countries and international organizations (Markusson, Kern, & Watson, 2010). If effective, such CO_2 capture and storage technologies (CCS) would allow the continued use of fossil fuels with reduced concerns about climate destabilization (Sathre, Chester, Cain, Masanet, 2012). However, despite its potential, the technology has yet to be proven as an integrated system at a full-scale so as to be an effective way of climate change mitigation, taking into consideration the viability, maturity and impacts. While CCS is seen as vital by some actors, others claim it is not an attractive option and may not be a necessary part of the transition towards a low carbon economy (Meadowcroft, Langhelle, 2009).

While CCS is now entering a phase of demonstration of full scale integrated systems in various locations around the world (de Coninck et al., 2009), there are still significant technical, economic, political and financial uncertainties about CCS (Markusson, Kern, Watson, 2010). As a result, the relevant uncertainties create challenges for the stakeholders who want to see CCS technology at a full scale deployment and as a tool for global climate change mitigation strategies. It is thus essential that decisions made by stakeholders for the full-scale deployment of CCS must be based on a clear understanding of social, scientific technical, political and economic dimensions. The clear understanding of these dimensions is crucial, since CCS needs government support to be part of the mitigation mix, investment choices by the business sector and public support. Taking into consideration the aforementioned, this thesis contributes to the understanding of the CCS stakeholders by providing an assessment of the barriers for the full-scale deployment of the technology.

1.2 Problem analysis

Taking into consideration that we are heading towards irreversible climate change because of global warming, mainly due to the high concentration of CO_2 in the atmosphere, the average temperature must be kept below 2^0 C rises. Moreover, the global population is expected to rise from 7 to 9 billion by 2050 (ZEP, 2012), which would mean that the world's energy demand is expected to increase by 50% over the next 20 years. Since energy consumption is going to continue to rise, fossil fuel power plants, heavy industry and refineries which are the largest emitters of CO_2, accounting for 52% of global emissions, or around 15 billion tones of CO_2 per year (ZEP, 2012) need to be addressed. For this great challenge, the solution seems to be a combination of energy efficiency, renewable energy and CCS. According to ZEP,2012 "it is impossible to achieve EU or global CO_2 reduction targets without CCS-providing 20% of the cuts required in the EU by 2030 and 20% of the global cuts required by 2050. CCS is the only available technology that can capture at least 90% of emissions from the world's largest emitters" (ZEP, 2012).

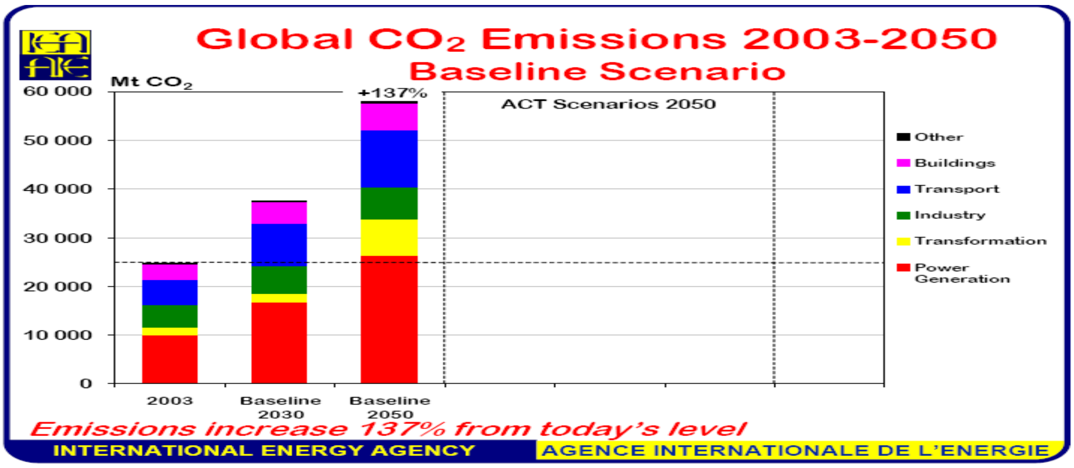

figure. 1 Global CO_2 Emissions Forecasts 2003-2050(IEA, 2006)

In the case of Port of Rotterdam and the City of Rotterdam, economic development depends to a large degree on energy and emission intensive industries and the power sector. The Port of Rotterdam is one of the largest industrial and petrochemical clusters in Europe and includes five refineries, two coal-fired power plants, two gas-fired power plants and some twenty chemical plants. Taking into consideration that the CO_2 emissions are expected to increase in the upcoming years, the Port of Rotterdam, the City of Rotterdam, port and industries' association Deltalinqs, and the DCMR Environmental Protection Agency committed themselves to Rotterdam Climate Initiative (RCI), which is aims to achieve a fifty percent reduction of CO_2 emissions in the Rotterdam region by 2025, as compared to 1990, to climate-proof and adapt the city to the consequences of climate change and to strengthen the Rotterdam economy(RCI, 2011). Despite maximum efforts on energy efficiency and renewable energy, over half of Rotterdam's CO_2 reduction goal can only be achieved through the capture of CO_2 emissions for re-use or permanent underground storage. Therefore, CO_2 Capture Storage and Transport (CCS) is considered to be the only technology capable of directly abating CO_2 emissions from both industrial facilities, such as refineries or steel plants, and fossil fuel power plants (RCI, 2011). However, CCS still remains in pilot project level and in order to meet the goals being set, the full-scale deployment of the technology is needed.

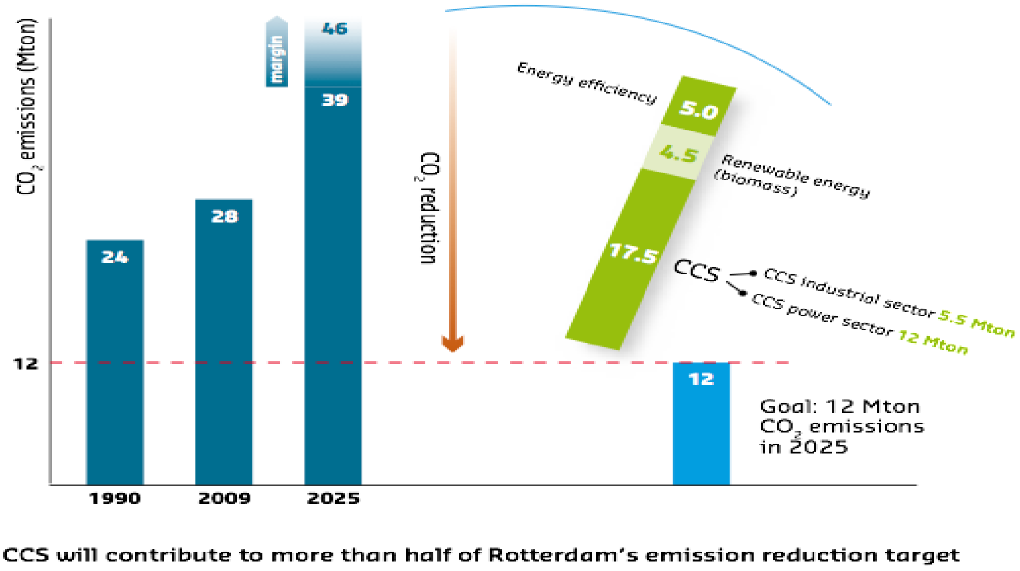

figure. 2 CO_2 Capture and Storage in Rotterdam (RCI, 2011)

1.3 Carbon Capture and Storage (CCS)

CCS technology involves separation of CO_2 from other gases emitted by power plants and industrial facilities. After transportation of the captured CO_2 by pipeline or ship to an appropriate facility, the captured CO_2 can either be re-used or stored underground. There are three ways to capture CO_2 from power plants: pre-combustion, post-combustion and oxy-combustion.

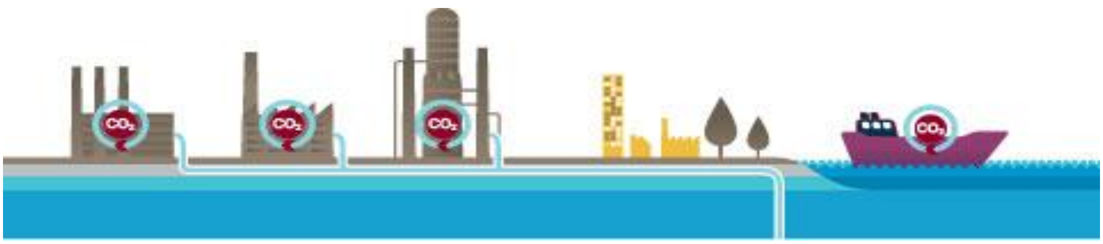

figure. 3 Carbon Capture Storage and Transportation (ZEP, 2012)

Pre-combustion technology captures CO_2 before the combustion in an energy plant, resulting in a cleaner fuel in the combustion process, thus in less CO_2 emissions. It is mainly used in new power plants, since it is relatively expensive to adapt into existing infrastructure (Huang, 2008).

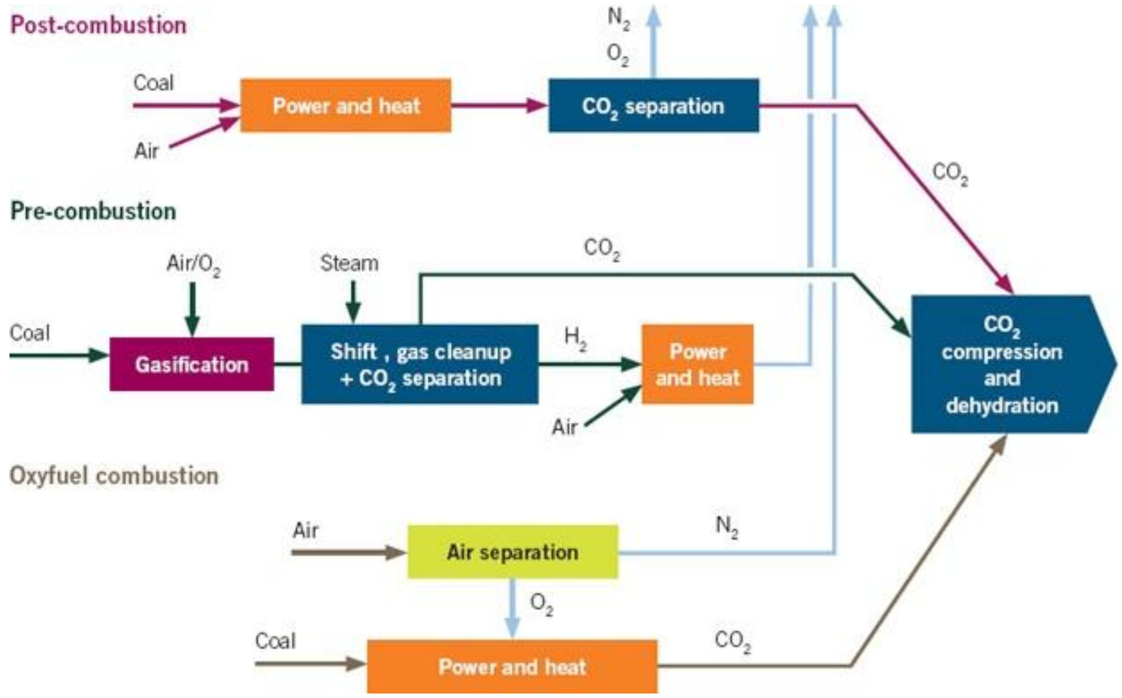

figure. 4 Technical options for CO2 Capture from coal power plants (EPRI, 2011)

Post-combustion technology captures the CO_2 after the combustion process in a power plant and can be applied in new and already existing plants, since the adaptation is relatively cheap, for the reason why only the processor needs to be adapted for the CO_2 capturing.

Oxy-combustion technology is based on the principle that if a power plant is fired with high-purified oxygen instead of air, the flue gas is mainly composed of CO_2 and H_2O. There are technical challenges in the adaptation of existing plants, because the heat transfer characteristics can change (Jordal, 2004) and the purification of oxygen on a larger scale might not be up to the standards for a medium oxy-combustion plant (Bolland, 2009).

The transportation of CO_2 can either take place with CO_2 has or liquefied mainly by pipeline transport and by ship. Dehydrated CO_2 can be transported by steel pipelines, because CO_2 does not corrode the steel. However, ship transportation can add flexibility and moreover current ships suitable for CO_2 transportation are compressed natural gas carriers or CO_2 can be transported in semi-refrigerated tanks.

figure. 5 CO_2 Transportation (ZEP, 2012)

Storage of captured CO_2 can mainly be geological, in sites such as depleted oil and gas reservoirs, deep aquifers and salt caverns. Saline aquifers though are the most promising solution for the long term storage of CO_2 (IEA, 2009). The captured CO_2 is injected in to the pores of sedimentary rocks, where it is trapped, or the CO_2 reacts with minerals also trapping it (IPCC, 2005). Depleted oil and gas fields are also capable of trapping or holding CO_2, with similar principle as with the saline aquifer storage. As oil fields approach the end of their commercial life, CO_2 can be used to maximize the extraction of the oil that remains in the field, a procedure known as Enhanced Oil Recovery (EOR). EOR is routinely practiced at on-shore oil fields, a practice driven by the economic benefits of EOR, rather than CO_2 storage. EOR with CO_2 can help to increase the yield of an average oil field with 50% (IEA, 2008).

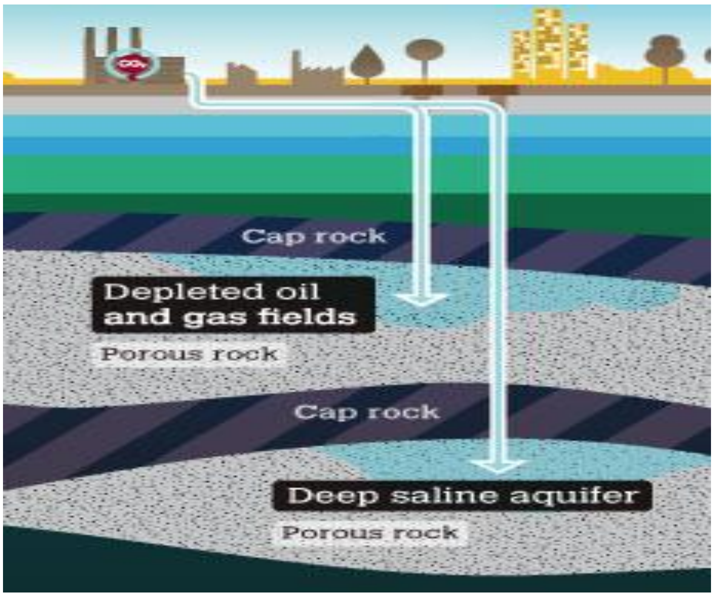

figure. 6 CO_2 Storage (ZEP, 2012)

CHAPTER 2

RESEARCH QUESTIONS

The stakeholders are now facing great challenges concerning the full-scale deployment of CO_2 Capture and Storage (CCS). One of the main challenges is that the number of scientific, technical, societal and economic barriers for the full-scale deployment of CCS globally is way too high. Governments need to be well informed of all those barriers since their support on CCS is of crucial importance for the formation of climate change mitigation strategies and the future of CCS itself. Of the same importance is the support of the energy industry and the business sector, since the high number of barriers for the full-scale deployment of CCS, make the decisions in terms of investment choices complex and risky. Apart from the necessary support of the government and business sector, the societal acceptability is equally important for the full-scale deployment of CCS, for the reason why the society is still not well informed about the existence of CCS and its role on reducing CO_2 emissions and moreover the associated externalities of CCS. Consequently, the governments, the business sector and the society face the following problem concerning the full-scale deployment of CCS:

The number of political, technical and economic and societal barriers for the full-scale deployment of CCS is too high

This leads to the following research questions:

1. What are the barriers for the full-scale deployment of CCS?
2. How to assess these barriers?
3. Which methodology fits best in assessing the barriers?
4. How do different stakeholders assess the barriers?
5. How these barriers can be overcome?
6. How the barriers are assessed by stakeholders in different locations globally?

By identifying the barriers for the full-scale deployment as well as the methodology for the assessment of these barriers, the perceptions of different stakeholders on the related barriers, this thesis aims to assessing the barriers so as to provide with insights the systematic decision making on CCS by the public and private sector.

CHAPTER 3

RESEARCH APPROACH

The approach of CCS in this thesis starts with technology assessment, the tools and research methods that have been cited in technology assessment literature, which might be helpful in assessing a new technology, such as CCS, its impacts, and can provide crucial information to policy makers, scientists and stakeholders so as to develop and deploy CCS technology. Next follows a literature review of assessment methodologies, which is conducted in order to identify which methods are appropriate for the assessment of new technologies and their impacts, such as CCS. Afterwards, a literature review from existing social science literature on CCS is conducted, so as to establish what is already known from a social science point of view and identify additional barriers and uncertainties related to the full-scale deployment of CCS.

In order to gain insights into the barriers and uncertainties and to make an assessment of the technology, different stakeholders in different locations around the world were asked to rank the identified barriers-uncertainties according to their relevance of importance and were also given the space to add and comment on barriers which they considered as crucial, by the use of internet survey and particularly by questionnaires. For the reason why there was only one response from the experts to who the questionnaires were sent, the research was alternatively carried on with interviews with experts on CCS in the Netherlands, covering the whole range of stakeholders: governmental, academic, business and environmental, in order to gain insights into the CCS technology and the related barriers and uncertainties for the full scale deployment. The experts interviewed were, similarly to the internet survey, asked to score the identified barriers-uncertainties according to their relevance of importance, to indicate any barriers-uncertainties which were not included by the writer, but are important to overcome for the full scale deployment of CCS, and to mention the effects of these barriers expected in the short, medium and long term. Furthermore they were asked how these barriers can be overcome, what would be an ideal mitigation mix strategy to ensure growth and economic development for the Port and City of Rotterdam, the feasibility of Port of Rotterdam to become Europe's CO_2 hub and the role of CCS in it, the perceived need for CCS in Rotterdam and finally who is the most ideal to take the lead for the full-scale deployment of CCS. Based on the ex-ante expectation of the writer that the expertise of the experts interviewed is similar, there is no weight application on the barriers during the scoring process.

3.1 Technology Assessment

The concept of TA was first developed in the United States in the late 1960s, and the Office of Technology Assessment (OTA) was established in 1969-1972. TA has its origins in the policy needs of the U.S. Congress as perceived by one of the committees of the House of Representatives (Guston, Sarewitz, 2001). As early as 1976 Joseph F. Coates defined TA as “the name for a class of policy studies which attempt to look at the widest possible scope of impacts in society of the introduction of a new technology. Its goal is to inform the policy process by putting before the decision maker an analyzed set of options, alternatives and consequences” (Coates, 1976) and as recently as 2001 he redefined the concept along that line as “a policy designed to better understand the consequences across society of the extension of the existing technology or the introduction of a new technology with emphasis on the effects that would normally be unplanned and unanticipated” (Coates 2001). Its goal was straightforward but by no means simple to achieve. TA was conceived as a concept to assist in public policy decision making. Its goal of informing and improving government decision making implied, of course, that the researchers also informed the thoughts and deliberations of a wider public concerned with policy toward new technologies (Guston, Sarewitz, 2001).

Classic TA was focused on forecasting technology change so as to predict its impacts on society (Rodemeyer et al., 2005). It aimed to support the development of policy managing those impacts, and was organized in advisory bodies like the Office of Technology Assessment in the US (Tran, Daim, 2008). The inherent difficulties in this task meant it worked best for specific and relatively mature technologies (Rodemeyer et al., 2005). Critiques have been leveled against the typical, often implicit, assumptions in classical TA about an autonomous and inevitable direction of technological change, assumed to be independent of society (Wynne, 1975).

A second wave of TA work in the 1980s and 1990s (Rodemeyer et al., 2005; Guston, Sarewitz, 2002; Schot, Rip, 1996) instead started from the realization that technology is generated and shaped by the people and institutions involved in its development. Technology was seen to co-evolve with the development of society. This brought an emphasis in TA activities on deliberation and involvement by a broader range of actors (Genus, 2006). The professed stance of TA also changed from distanced observation to involvement with technology development and technology governance, and from forecasting to a more modest insistence on iterative, continuous assessment (Markusson et al., 2010).

A systematic review of existing social science research on CCS reveals that it has so far focused on two main areas (Markusson et al., 2010). Firstly, there are publications exploring public understanding and acceptance (Desbarats et al., 2010). Secondly, there is work based mainly in economics, particularly the modeling of deployment scenarios and assessments of the impact and cost efficiency of CCS and other climate mitigation options (Markusson et al., 2010). There is only a small social science based literature that is more directly concerned with CCS innovation and technology development. There is some research on learning curves (Rubin et al., 2010): quantified models of technology costs that are usually forecast to decline as a function of deployed capacity. These studies are intended to measure technology learning and improvement in the form of decreased costs (Markusson et al., 2010). But in the absence of reliable CCS cost data, they are reliant on inferring lessons from cost trends in other technologies, for example Flue Gas Desulphurization technology. When applied to CCS, such models also rely on uncertain assumptions about current CCS costs. Ultimately, learning curve analysis can only tell us a limited amount about CCS innovation processes (Markusson et al., 2010). There is also limited literature on CCS innovation systems which has begun to explore the role of actors and institutions (van Alphen et al., 2010).

De Coninck et al., made an assessment of the key determining factors for the acceptability of CO_2 capture and storage (CCS) in Europe addressing technical, economic and scientific questions and Markusson et al., developed an interdisciplinary framework to assess technical, economic, financial, political and societal uncertainties about CCS. However, there is still plenty of scope for analysis and assessment of barriers that hold back the full-scale deployment of CCS technology, regarding technical, economic, financial, political and societal aspects.

CHAPTER 4

METHODOLOGY

4.1.1 Towards Multi-Criteria Analysis (MCA)

At least four methodologies are available for assessing Carbon Capture and Storage technology and its viability: (i) conventional environmental assessment (such as environmental impact assessment (Morris, Therivel, 2001); life cycle analysis (Curran, 1996)); (ii) multi-criteria approaches (such as multi-criteria mapping (Stirling, Mayer, 2001); multi-attribute decision analysis (Keeney, Raiffa, 1993); (iii)economic evaluation (e.g. cost benefit analysis (Pearce, Turner, 1989)); and (iv) discursive and deliberative approaches (such as citizens panels, consensus conferences, citizens juries inter alia (Renn et al., 1995; kasemir et al.,2003). Table I summarizes some of the main strengths and weaknesses of these different approaches to appraisal, using a list of desirable features of an evaluation methodology compiled from the literature by Stirling and Mayer (2001). After a comparison, the discursive and MCA approaches seem to be the most suitable for understanding the complex and different perspectives of CO_2 Capture and Storage and its barriers for the full-scale deployment. In a Multi-Criteria Assessment framework a small number of professional stakeholders are interviewed and asked to score scenarios against a set of evaluation criteria (barriers) according to their perceived importance. MCA provides a systematic means of representing different perspectives in an assessment process, allowing stakeholders the flexibility to explore options with their own criteria, weighting and scores (Gough, Shackley, 2005). This method is easily understandable, flexible, and transparent and does not depend on the technical expertise of the participants allowing a wide range of perspectives in the assessment. However, this assessment method is not able to reveal a real CCS future but its objective is to assess the technical, economic, financial, political and societal barriers for the full-scale development of CCS so as to support decision makers.

Multi-criteria analysis (MCA) is a popular tool in Dutch environmental impact assessment (EIA). Environmental Impact Asessment is a well established institution in the Netherlands and production of EIA's by environmental consultants often use MCA in order to support decision making, regarding comparison of alternatives and their evaluation. In the last 5-10 years, further quantification of environmental management, an increase in the size and complexity of projects, an increased public participation in the decision-making process has created the need to communicate large amounts of information in a straightforward and transparent way (Janssen, 2001). This has stimulated a dramatic increase in the use of MCA. Some examples of MCA in Dutch EIA are siting and design of a storage facility for polluted sediments in the Hollandsch Diep, river development Zandmaas, road train and water transport in the Amsterdam-Utrecht corridor. Another example is an appraisal for United Kingdom Nirex Limited of potential UK sites that could be investigated for their suitability as radioactive waste repositories (Dodgson, et al., 2001). Finally, examples of technology assessment by means of MCA can be found in health technology, for the assessment of new and existing medical technologies.

Desirable features of the evaluation methodology	Environmental assessment (e.g. EIA/LCA)	Economic evaluation (e.g. CBA/cost-effectiveness analysis)	Discursive assessment (Focus groups, etc.)	Multi-criteria approaches (e.g. MCM/MADA)
Capacity to include a number of perspectives and values	Limited-indirectly through use of sensitivity analysis	Limited-performance measured through economic efficiency which may not be the priority of all parties	Good: participants encouraged to openly express preferences	Good: stakeholders can add options, select criteria, apply their own weightings and scores
Transparency	Potentially good but depends on transparency of assumptions and data	Theory and method is clear, but valuation of non-market goods by contingent valuation methods is frequently non-transparent. Based on economic theory, results rely on data	Potentially good but dependent on researchers' interpretation but highly context specific which may limit communicability	Good depending on aggregation method: performance matrices may be easily examined by participants and others
Considers the multi-dimensional aspect of the problem in a flexible manner	Limited to quantitative indicators of environmental, energy or material impacts	Costs and benefits expressed in monetary terms which may not be appropriate for all consequences of the policies or projects	Potentially very good but often focuses on socio-political issues; not always amenable to quantitative analysis	Good: qualitative or quantitative information can be included such that non commensurable factors are not forced into one format
Systematic framework	Yes but limited to physical environment	Yes	Weak; can include a large number of different methodologies and underlying theories	Yes
Adds to the understanding of the problem	Good but limited to part of problems, not always that which is of most importance	Limited: CBA attempts to deliver an optimal solution to resource allocation under one criterion. It therefore brackets-out alternative problem definitions	Can be good: helps to understand how the problem is framed according to different perspectives	Good: allows the exploration of how different perspectives affect the performance of options. Somewhat limited in that it may not include more 'intuitive' and informal dimensions of perceptions
Stakeholder engagement	Limited to technical experts	Often involves public participation but the valuation of qualitative impacts in monetary terms via such methods	Very good	Good: both experts and lay people can be involved and understand the

		as CVM is not easily understood		process
Ease of carrying out procedure	Requires much detailed information-often not available +/ highly uncertain	CVM survey may be time consuming and must be carefully performed to avoid bias; requires experienced practitioner. Other data required is often uncertain	Requires high level of skill in facilitation	Method is relatively straightforward, and can be applied as a group process or through the use of one to one interviews

table. 1 Comparison of different approaches to appraisal

Source: Gough, Shackley, 2005

41.2 Multi-Criteria Assessment

Multi-criteria assessment covers a variety of non-monetary evaluation techniques sharing a basic framework under which a number of alternatives can be scored against a series of defined criteria and to which users attach weights reflecting the relative importance of each criterion (Dodgson et al., 2001; Keeney, Raiffa, 1993). Its role is to provide a framework to enable decision makers to overcome difficulties in handling large amount of complex information in a consistent way. MCA establishes preferences between options by reference to an explicit set of objectives that the decision-making body has identified. Since the objective of this thesis is to assess the barriers for the full-scale deployment of CCS, the use of multi-criteria analysis will help in doing so, by providing the stakeholders' sufficient opinion, although the findings from the small number of stakeholders can only be considered as indicative.

The first step in the MCA process is to identify the objective, which in the case of Rotterdam is the role of CCS in reducing CO_2 emissions with 50% in 2025 compared to 1990, as part of climate change mitigation strategy. In the EU, the objective is to limit global temperature increase to a maximum of 2^0 C above the pre-industrial level, implying global green-house gas reductions of 15-50% by 2050 compared to the emissions in 1990, and 60-80% reductions for developed countries (European Commission, 2007b). The second step is to identify the options for achieving the objectives. For this reason, this thesis identifies 3 options, a short-term scenario for full-scale CCS deployment (up to 2020), a medium-term scenario (2020-2030) and a long-term one (2030-beyond). The following step in the MCA process is to identify a set of criteria against which the full-scale deployment of CCS scenarios will be assessed. These criteria in this thesis are the barriers identified in the literature review, but the stakeholders are given room through the use of MCA to add furthermore possible criteria. The criteria are all evaluated on a relative scale by allocating 0-100 points to each criterion across the options, such that higher scores always signify a less favorable performance against the criteria. Scoring is based on the subjective opinions of the respondents. The fourth step in the MCA process is the rating by the stakeholders of the performance of each option/scenario against the criteria, fifth follows the assignment of weights across the criteria. The 6th step of the process is the combination of the scores and weights and last one stands the examination of the results and review.

Since the ultimate product of MCA procedure is the ranking of options/scenarios against identified criteria (in this case barriers), the use of MCA and its results will help fulfilling the objective of this thesis, which is to support decision makers and provide them with useful insights on the barriers for the full-scale deployment of CCS in the future.

After having explained the main issues of the methodology chosen (MCA) in order to assess the barriers and uncertainties for the full scale deployment of CCS, in the next chapter there is the findings from the literature review conducted from existing social science literature on CCS so as to establish what is already known from a social science point of view and identify gaps regarding technical, economic, financial, political and societal aspects of CCS.

CHAPTER 5

LITERATURE REVIEW

Introduction

The literature review is the selection of available documents (both published and unpublished) on the topic of interest, which contain information, ideas, data and evidence. The main purpose of the literature review is to identify the gap in the research that the thesis is attempting to address, positioning it in the context of previous research. Furthermore, the literature review aims at evaluating and synthesizing the information and concepts related to the research and producing a rationale or justification for the specific study. Literature review contributes to the understanding of the topic and to the creation of the framework under which the research extends or enhances the studies that have already been done on the related topic. Therefore, the approach of the barriers and uncertainties related to the full-scale deployment of CCS in this thesis starts with a literature review from existing social science literature on CCS so as to establish what is already known from a social science point of view and identify gaps regarding technical, economic, financial, political and societal aspects of CCS. Furthermore, a literature review of assessment methods was conducted, in order to identify which methods are appropriate for the assessment of new technologies and their impacts, such as CCS. The literature review conducted on CCS resulted in the barriers and uncertainties described at the following section.

5.1 Barriers and uncertainties for the full-scale deployment of CO_2 capture and storage (CCS)

5.1.1 Lack of robust-transparent legal framework

While CCS is now entering a phase of demonstration of full scale integrated systems in various location around the world (de Conick, et al., 2009), there are still significant political uncertainties about CCS. Markusson et al. in 2010 made an assessment of CCS viability on a socio-technical framework identifying key uncertainties. Between other uncertainties for the development of CCS, policy (specific policy instruments which could help CCS to develop) as well as politics (the political processes of getting acceptance, legitimacy and continued support for CCS, questions of power, lobbying, etc) are important (Markusson et al., 2010). The importance of these factors lies in the fact that the future development of CCS will depend on explicit political and policy choices as "a strong and regulatory push and/or a significant price for carbon emissions will be required to develop commercial applications" (Markusson et al., 2010).

Consequently, a number of issues or 'gaps' in the present international and European framework need to be addressed. Back in 2008, the European Commission produced a draft of proposed legislative measures called the "climate action and renewable energy package, aimed at delivering the EU's greenhouse reduction and renewable energy objectives for 2020 (de Conick, et al., 2009). As part of the package the Commission proposed a Directive on the geological storage of carbon dioxide, along with a detailed Impact Assessment and a statement on supporting early demonstration of sustainable power generation from fossil fuels (European Commission, 2008a, b, c, respectively). The proposed Directive will, if adopted, establish a bespoke legal framework to regulate the storage of captured CO_2 in the EU and its goal is to cover the entire life-cycle of a geological storage site, from site selection and operation requirements, through to closure obligations and the transfer of post-closure responsibilities to competent authorities of Member States but only after there is near certainty that the possibility of leakage has been reduced to zero (de Conick, et al., 2009). The most significant challenge for legislators is the long term regime for the storage of CO_2.The proposed Directive furthermore requires the new power plants will be built with 'capture-ready' technology, thus being equipped with CO_2 capture plant and with suitable storage sites, and identified transport routes. Although the Directive's focus is on storage, it will also mesh with existing legislative instruments, which will be amended so that they explicitly cover the capture and transport components of CCS activities. In doing so, it is intended to clarify existing legislation and remove barriers that currently restrict the large-scale development of CCS facilities, particularly in relation to waste, water and industrial emissions legislation (de Coninck, et al., 2009). If CCS is to be deployed on a European level, in synchronization with policies that incentives investment, legal frameworks should be established to regulate the implementation and operation of CCS (Mikunda et al., 2010). It is argued that "a clear and predictable long term framework is necessary to facilitate a smooth and rapid transition to a CCS-equipped power generation from coal (European Commission, 2007a).

Given that the objective is to limit global temperature increase to a maximum of 2^0 C above the pre-industrial level, implying global green-house gas reductions of 15-50% by 2050 compared to the emissions in 1990, and 60-80% reductions for developed countries (European Commission, 2007b), CCS may have to play a significant role in meeting long-term emission targets. Therefore, the long-term deployment of CCS will depend on the future political need to carry out strict emission reduction targets, possibly on a global level, since it is difficult to envisage a unilateral strict emission reduction policy over time from the EU only (Haugen et al., 2011). This creates challenges for those actors who want to see CCS technology developed and deployed. This is a problem for policy makers designing policy for CCS as well as broader energy and climate mitigation. This is crucial as CCS will need government support to be part of mitigation mix (Markusson et al., 2010).

On a national level, governments in order to increase the involvement in the CCS market can take three possible roles, a supervisor role, an investigator and an active participant/ owner role. According to Schokkenbroek H. et al., 2011, "the government should focus its incentives measures mainly on the capture and storage aspects of the value chain. A large scale investment programme, associated with the participant /owner role is considered undesirable" (Schokkenbroek H. et al., 2011).

Current policy frameworks, for instance the EU ETS, are not sufficient to encourage investment since political, policy and regulatory decisions about policy support, carbon prices, carbon reduction goals, liability rules, possible inclusion in Clean Development Mechanism (CDM) and EU ETS, etc. massively impact on the economic and financial viability (Markusson et al., 2010).

To conclude, the policy and political barriers are the lack of specific policy instruments which could help CCS to develop, such as the political processes of getting acceptance, legitimacy and support for CCS, the unilateral strict emission reduction policy, the inclusion of CCS in EU ETS and CDM and support for carbon prices. In addition, the legal barriers concerning the full-scale deployment of CCS is the lack of robust and transparent regulation for the storage and transportation of captured CO_2 in the EU, the obligations and responsibilities of Member States in relation to waste, water and industrial emission legislation and liability rules.

5.1.2 Economic and financial viability

One of the key uncertainties of CCS is its future economic and financial viability for investors. The associated risks make CCS less attractive than investing in alternatives even if the technology is economically viable. According to Markusson, et al., "economic and financial viability is a key uncertainty for businesses as well as policy makers and will determine their willingness to invest in CCS" (Markusson, Kern, & Watson, 2010). Improving the economic and financial viability is an important rationale for policy support. The European Commission's own analysis of 2007 suggests that there is a risk that CCS will not be deployed at a sufficient scale sufficiently rapidly to meet climate change objectives without the implementation of economic incentives and/or regulation (in addition to the Emissions Trading Scheme) (de Coninck, et al., 2009). The economic and financial viability of CCS apart from political factors and policy frameworks is also influenced by factors such as fuel reserves and prices, electricity prices, capital costs. Moreover political, policy and regulatory decisions about policy support, carbon prices, carbon reduction goals, liability rules, possible inclusion in CDM and EU ETS, etc. massively impact on the economic and financial viability (Markusson et al., 2010).

For many, the ideal vehicle for funding the demonstration and subsequent CCS plants would be the EU emissions trading scheme (EU ETS). However, almost all proponents of CCS agree that the EU ETS is not yet sufficient to finance CCS because carbon prices are not high or stable enough (Scrase, Watson, 2009). The total costs for capture, transport and storage are calculated in the range of 25-57€/ton, with the largest uncertainty in the capture. This is in the same range as the estimates by the European Commission, which estimates that the price of emission rights from the ETS should be in the order of 39-45€/ton in order to jumpstart CCS (Vergragt, 2009). It is uncertain if the ETS alone is an adequate incentive to achieve commercial deployment of CCS by 2025. Currently ETS prices are considered too low and too volatile to trigger full-scale deployment (Rotterdam Climate Initiative, 2011). The price of emission allowance is not high enough to lower its competitiveness. For the same reason, no CCS is to be installed either since its economics are mainly dependent on the allowance price. CCS is to be retrofitted to all existing capacities of coal plants since the revenues from trading emission allowances now overweigh their investment and fixed costs (Koo, Han, Yoon, 2011). Therefore other options are required-at least in the short to the medium term. In designing alternative financing schemes, the government will need to take account a range of factors, not least the uncertainty about the eventual costs of CCS (Scrase, Watson, 2009). According to the RCI "additional incentives, such as an emission performance standard (a CO_2 norm per produced kWh), are needed to ensure the successful implementation of CCS. At the same time an international level playing field will have to be maintained" (RCI, 2011:8).

The European Commission funded Acceptance of CO_2 capture, Storage, Economics, Policy and Technology (ACCSEPT, 2007) was primarily on the acceptability of CCS within the EU 27 nations (de Coninck, et al., 2009). According to the project's results about the Stakeholder Perceptions of CO_2 Capture and Storage in Europe, "There is clearly strong support from all stakeholders in all countries for stronger incentives to support the further development and implementation of CCS within the EU. Most important among these are an early commitment to extend the EU ETS beyond the Kyoto reporting period with stronger national emissions caps. Secondly, rather than trying to encourage consensus, it is important to continue to pursue an active dialogue and effective sharing of information and new scientific and technical data as it becomes available" (ACCSEPT, 2007:4). Additionally, it has been stated that the only way in which public investment will improve efficiency is if the government is best informed about probability of future demand of CO_2 (Mikunda et al., 2010). The most appropriate incentives for CCS development in home countries according to the ACCSEPT project is Research, Development& demonstration with over 90% of respondents in favor. This followed by early commitment to extend the EU ETS with tighter emissions caps (77% in favor, 8% against). The third most popular option is a requirement for electricity generators to supply a given percentage of zero- or low-carbon electricity.

Apart from the inclusion of CCS in the EU ETS, there may be some significant benefits offered by including CCS in the CDM, based around what are considered the two main challenges to realizing CCS in the medium-term, namely achieving technical learning and cost reduction through widespread deployment; and providing successful storage of CO_2 in a range of media locations worldwide. Inclusion of CCS in the CDM could therefore provide useful bridging finance to support a CCS technology development pathway over the next 15-20 years (Zakkour et al., 2011)

As yet, however, there have been no positive investment decisions regarding potential large-scale demonstration projects; in fact, several proposals have been already been cancelled because of increasing costs and disappointing projected revenues (the Magnum project of Nuon in the Netherlands; the Miller-Peterhead project of BP in Scotland; and the Tjellbergodden project in Norway) (de Coninck et al., 2009). In the UK, the main economic problem for CCS is that no financing arrangements are promised beyond those for demonstration plant. It may be some time before the carbon price in the EU ETS is high or certain enough for investors to rely on it as a source of finance (Scrase, Watson, 2009).

According to the RCI, both the national government and the EU will have to play important roles in financing these developments. National government funding and regulations, and European Union policies (ETS) are crucial to take off. The only reason why CCS is implemented is to reduce CO_2 emissions. Hence, the economic feasibility of CCS depends upon the readiness of governments to internalize the external costs of CO_2 emissions (de Coninck et al., 2009).

In conclusion, the main barriers and uncertainties regarding the economic and financial viability of CCS is the high investment costs of CCS for widespread deployment, the associated risks for investors, the low and unstable carbon prices, the lack of economic incentives, the dependence of CCS on the allowance price, the need for inclusion of CCS in EU ETS and CDM, the need for extension of EU ETS with tighter emission caps, the need for public investment and national government funding and finally the need for additional incentives, such as an emission performance standard.

5.1.3 Carbon lock-in

The concepts "lock-in" and "path dependency" have been developed by Brian Arthur and Paul David to describe how technologies and socio-technical systems could eventually become suboptimal solutions for new societal challenges, because of the vested institutional interests and the sunk costs investments in infrastructure and knowledge (Arthur, 1985, 1989; David, 1985). Fossil fuel lock-in would mean that it would become eventually even more difficult to move away from fossil fuels to renewable and conservation. And indeed, it is hard to see how investments of billions of Euros in capture, infrastructure for transportation, storage, monitoring and safeguarding will not be used in the future as an argument to continue CCS rather than move to renewable (Vergragt, 2009). Industry is arguably already discounting the price of CO_2 on the EU ETS, thus favoring new coal rather than gas power plant build, which could thereby enhance carbon lock-in and further increase the tendency for politicians to argue for less demanding carbon cap (Lockwood, 2008).

One of the arguments put forward by the Greenpeace is that CCS technologies risk perpetuating the 'lock-in' of centralized energy systems (Greenpeace, 2008). Markusson and Haszeldine, 2008, note there is more than one lock-in scenario to consider, depending both on the 'capture readiness' of new capacity and whether or not CCS actually becomes available later. The government of the UK argues that this capture readiness will help prevent carbon lock-in, but if CCS fails to deliver then the reverse may be more accurate (if the promise of CCS is used to justify new coal fired capacity in the short term) (Scrase, Watson, 2009).

In his case study from the Netherlands, Vergragt, 2009 raises two major questions: the first is how it can be explained that CCS has been emerging so fast as a major technological and policy tool for CO_2 reduction, as compared to other options like energy conservation and reinforcement of the fossil fuel lock-in, which could be held responsible for the slow emergence of sustainable energy sources. As to the second question, about CO_2 lock-in, it is clear that CCS is driven by main business actors who have vested interest in the fossil fuel industry, especially in coal, less so in oil. A complete transition to conservation and renewable energy as envisaged by Greenpeace does not have a lot of support from those business interests (Vergragt, 2009).

This could be called lock-in of fossil fuels, especially of coal. CCS does many things: it 'buys' time before the necessary switch to renewable and conservation; for some it delays nuclear energy; it brings to the table powerful actors, and last but not least It facilitates coal power plants, the most pollutant form of electricity generation (Vergragt, 2009).

In conclusion, fossil fuel lock-in and especially of coal would mean that it would become eventually even more difficult to move away from coal to renewable energy and conservation, since the billions of Euros already invested in CCS will be used as a strong argument to continue CCS instead of moving to renewable energy. Furthermore, the main business actors who drive CCS technology have vested interest in the fossil fuel industry, especially in coal and the use of CCS facilitates coal power plants, thus leading to fossil fuel lock-in.

5.1.4 Gaps in knowledge

A great challenge for the deployment of CCS lies in the timing of information availability. Since there still not exist any large carbon capture (CC) plant which can possibly have other emissions compared to a regular coal-fired plant, the providing to the authorities with all possible details is challenging, so as to make a solid assessment of the details and also write the definite values in permit. The ultimate details can only be provided after starting the operation of the CC plant, but based on pilot plants the most relevant emissions can of course be provided (Huizeling et al., 2011). This is the true illustration of the demonstration character. This means that some room has to be included in permit values which can be tightened after the first years of operation (Huizeling et al., 2011).

Numerous studies on the costs of CCS exist in the peer-reviewed literature, including economic modeling using various models, the present state of affairs having been summarized in several reviews (IPCC, 2005; MIT, 2007; IPCC, 2007). Behind this wealth of information, however, many gaps and uncertainties still exist (de Coninck et al., 2007; MIT, 2007). In their paper The Acceptability of CO_2 capture and storage

(CCS) in Europe: An assessment of the key determining factors, Part 1. Scientific, technical and economic dimensions, de Coninck et al., 2009, made an assessment of the main information gaps and problems related to CCS.

Referencing same work: Even though there is a large number of studies regarding engineering costs, most of those studies are based on data which become from only a few base studies. The considerable body of literature creates the impression that many independent sources converge on cost estimates, but in reality, those many sources share a few common origins (de Coninck et al., 2009).

Confidentiality: The CCS technologies are mostly developed from existing commercial technologies instead of the public sector and R%D programmes. Consequently, the companies involved in developing CCS technologies protect their knowledge, information and agreements by keeping them confidential in order to add value to themselves. Detailed information on CCS technologies and their costs is, therefore, not fully available in the public domain and is difficult for independent researchers to assess the validity of assumptions in their cost models without access to such data (de Coninck et al., 2009).

Technology advocacy and optimism: Based on the experience of other energy technologies, the experts working on developing a certain technology tend to praise the advantages of the technology in which are involved in and to criticize the existing competing technologies. Those closely involved in developing a particular technological option frequently need to attract policy attention and resources, and this may lead them to underestimate the costs, leading to information bias (de Coninck et al., 2009).

Changes in fuel and material costs: The changes in oil, gas and steel prices are often not taken into consideration by most of the studies, which assume pre-2005 prices, which has as a result the misinformation in steel intensive options, because of rising costs of materials. MIT(2007) estimates that the rise in construction costs inceases the capital costs of power plants by 25-35% relative to the situation in 2004 (de Coninck et al., 2009).

Concluding, the full scale-deployment of CCS lies in the timing of information availability, the fact that the lack of any large CCS plant cannot provide the authorities with details on emissions, the information gaps in literature, the referencing of studies on same work on cost estimates just from a few base studies, the confidentiality of information which are not fully available in the public domain by the enterprises. Furthermore, the fact that studies don not take into account the changes in fuel and material costs and finally the technology advocacy and optimism from experts working on CCS, which may lead to underestimate of costs and information bias.

5.1.5 Variety of CCS pathways

In their socio-technical framed assessment of CCS viability, Markusson et al., 2010, identified as an uncertainty for the viability of CO_2 capture, transport and storage the variety of CCS pathways. Particularly, for each of the components of the capture, transport and storage chain, there is diversity in technology, for instance different technologies for capture, storage and modes of transport. Based on technology driven differentiation, some studies compare different CCS technologies against each other, while other studies concentrate on one specific technology and/or compare CCS routes against alternative low CO_2 emission technologies such as energy production by renewable energy sources. The three capture technology routes, post-combustion, oxy-fuel and pre-combustion constitute the first differentiation criteria (Zapp et al., 2012). This technology diversity and the relevant uncertainty as to what kind of technology to invest in, raises dilemmas for the stakeholders (e.g. governments, investors), although the competition between different technologies is normal and good for learning and develop know-how. However, an early selection may become quite soon outdated, standing actors with uncompetitive assets, and/or locking CCS into inferior technologies. For the aforementioned reasons thus, governments need to balance the need for experimentation with the need for fast development and deployment and perhaps premature closure of technological choices. There is also a need for policy supporting technological diversity to maximize learning and the chances of constructing good technology/ avoiding lock-in to poorly performing technology (Markusson, Kern, Watchon, 2010). Amongst proponents of CCS, there is an active debate about which particular technologies are the most desirable. Many organizations maintain that all variants should be supported-and that it is too early to tell which (e.g. pre- or post-combustion) will turn out to be the most technically and /or economically attractive (Scrase, Watson, 2009).

5.1.6 Carbon leakage to non-ETS countries

In her paper Unintended Consequences: Climate Change Policy in a Globalizing World, Schreuder, 2011, refers to the EU Emission Trading Scheme (ETS); the 'cap-and-trade' system implemented by the EU in order to comply with agreed to carbon emissions reduction targets under the United Nations Framework Convention on Climate Change (UNFCCC)'s Kyoto Protocol (1997). As the EU has been 'going-it-alone' with mixed success in terms of complying with the Protocol's binding emissions reduction targets, the ambitious energy and climate policy adopted by the EU has led to 'carbon leakage' and in some instances to relocation or shift of production of energy-intensive manufacturing to parts of the world where carbon reduction commitments are not in effect (i.e. the United States, China, India, Brazil and other 'emerging' economies) (Schreuder, 2011). Since energy intensive industries are largely dependent on coal for power generation, which is an abundant and cheap energy source and at the same time the impact of fuel and electricity prices increases and volatility, this may have important implication for location decisions in locations where carbon constraints are not in effect. Carbon leakage occurs mainly between Annex I and non-Annex I countries of the UNFCCC and between those Annex I countries that have committed to CO_2 emissions reductions under the Kyoto Protocol and Annex I countries that did not ratify the Protocol and therefore did not commit to binding emissions reduction targets . Because of the increased costs of energy-intensive products due to carbon constraint policies, their manufacturers can invest in more energy-efficient plants including CCS so as to reduce their carbon emissions. Alternatively, they can buy allowances provided on the carbon market on a reasonable price. If they cannot afford to buy allowances or carbon permits to facilitate production then future business prospects are affected and market share of the company will fall. According to Schreuder, 2011, "The fourth and final option is to relocate production outside the carbon constraint region. The latter, is the most damaging to the prospect of controlling global CO_2 emissions".

CO_2 reduction policies are probably going to increase the costs of production in countries for which abatement strategies are already in effect, which can result in allocation to non-abatement countries. Carbon leakage can be triggered by direct carbon costs (price for carbon allowance or carbon credits) and indirect carbon costs resulting from higher power or electricity prices. Taking into account that carbon emissions by Chinese producers are far higher and more than double those of European producers, EUROFER arrives at the conclusion that the EU ETS leads to carbon leakage to non-ETS countries (Schreuder, 2011). The increased production costs for energy-intensive products in combination with the option of manufacturers to allocate to non-abatement countries, stands as an additional factor which makes the deployment of CCS harder.

5.1.7 Renewable energy competition

Koo, et al., 2011, in their paper Integration of CCS, emissions trading and volatilities of fuel prices into sustainable energy planning and its robust optimization, presented a case study of the South Korean peninsula in order to demonstrate applicability of the proposed methodology, as well as insights that it offers. According to the case study results, power plants that use fossil fuels are still more competitive than RES-based plants when the emission allowances are traded at the price of \$13/ton. However, wind power plants become more attractive as the price rises to the level of \$20/ton or higher; other RES technologies appear to need further reduction in capital costs to compete against CCS-installed plants that use fossil fuels (Koo et al., 2011). Moreover, they claim that wind plants are now competitive since they emit the least amount of CO_2 per TOE of energy generated; their costs are also the lowest among RES-based power plants. Consequently, they can minimize the costs with the addition of revenues from selling the emission allowances to neighboring regions. They conclude in that CCS is to be retrofitted to all existing capacities of coal plants for the reason why the investment and fixed costs are overweighed by the revenues from trading emission allowances.

Regarding the German situation, the renewable electricity production is distinguished between a mix of all renewable on the one side, and the wind-off-shore power plants on the other. According to Viebahn et al., 2007:128, “a mix of renewable energies can become more economic than CCS based gas-fired power stations. The intersection with coal-fired power stations including CCS moves later to 2033. With smaller price increases the intersection moves to 2050. Electricity from wind-offshore power alone will become cost competitive around 2020”. When a comparison is made between CCS technologies and renewable electricity, the CCS technology emit per kWh more than generally assumed in clean-coal concepts (total CO_2 reduction by 72-90% and total greenhouse gas reduction by 65-79%) and much more if compared with renewable electricity. However, CCS could lead to a significant absolute reduction of GHG-emissions within the electricity supply system (Viebahn, 2007). Concluding, the renewable could develop in a faster rate and depending on the market development and the growth rates, in the long term they could be cheaper than the CCS based plants.

5.1.8 Public acceptance/resistance

Another key uncertainty around the development of CCS is whether CCS will be seen as a legitimate technology for climate change mitigation (Markusson, et al., 2010). The existing literature stresses that societal acceptance is widely recognized as an important factor influencing the successful development and diffusion of new technologies (Huijts, 2007). Research by Dutch researchers from the Technical University Eindhoven links social acceptance of a new technology strongly to trust in the actors (Huijts et al, 2007). Public acceptance often depends on information from media and stakeholders and trust in key institutions is of key importance (Markusson, et al., 2010).More information could help to stabilize opinions, but different research shows different outcomes: in Japan more information lead to more support for CCS, and American researchers reported more opposition. The conclusion is that it is not definite if people will accept CCS in the end (Vergragt, 2009).

Building public confidence is a prerequisite for further development of CCS. As long as the public is not convinced of the necessity and the safety of any new technology, it remains reluctant to accept such developments (Rotterdam Climate Initiative, 2011). At present the public knows very little about CCS and it is not easy to change that. The relatively small-scale storage of CO_2 under a residential area in Barendrecht, Netherlands and its creation of a lot of concern with population and local politicians brought the issue to public attention in a negative way. The problems with public acceptance surfaced around the CCS project in Barendrecht. Shell applied for a € 30 million subsidy for injection and storage of very pure CO_2 from its Pernis oil refineries. The population is not happy with storage “under their backyard” (Vergragt, 2009). The earmarking of reservoirs for CO_2 storage demonstration projects provided much-needed clarity and provided an incentive to all parties move forward. Also, given the problem with public acceptance, local governments and emitters wanted to know which reservoirs were preferred storage locations, so that they could start a dialogue with the local population (Schokkenbroek et al., 2011).

In the ACCSEPT survey, the results about public perceptions of CCS in home country and the EU show that Norwegian stakeholders perceive that their public will strongly support CCS (48%) with a further 39% moderately supportive. Only 4% of respondents thought that there would be moderate opposition to CCS, and no respondent thought there would be strong opposition. Respondents in the UK and the Netherlands also expected little opposition (roughly 10% of which only 1-2% expected strong opposition). Respondents from Denmark and Germany were the most likely to express the view that there would be greater public opposition to CCS than the sample average: 35% and 31% would be moderately opposed respectively with a further 9% and 4% strongly opposed (ACCSEPT, 2007).

Because the risks from climate change due to fossil fuel emissions are larger and far more difficult to manage than the risks of CCS, the risk of leakage of storage should not impede CCS development overall. Whatever the physical reality of risk, as perceived by scientists, industrialists or regulators, if stakeholders are not convinced of that reality, storage may face acceptance problems (de Coninck et al., 2009). Since the public endorsement is crucial prerequisite for the success of CCS, much need to be done in the form of information dissemination and communication (Vergragt, 2009). Complete and balanced information on CCS should be made easily accessible to the public (RCI, 2011). CCS remains relatively unknown for the wider public, and is mainly known in policy circles, in the related business and in some academic circles. This is remarkable because there might be wide societal resistance, ranging from "NUMBY" (not under my backyard) to resistance against to large-scale infrastructural works like CO_2 pipelines, as well as resistance against the long-term liabilities (Vergragt, 2009).

5.1.9 Inclusion of CCS in ETS

Europe has emerged as a leader in the emissions trading industry with the EU ETS being the world's largest simple market for CO_2 emission allowances, accounting for approximately 98% of the global transactions for 2007 (Daskalakis et al., 2009). The cap on emissions in phase two of the EU ETS (2008-2012) is some 6.5% lower than for phase one (2005-2007) , however the economic crisis has radically altered the picture and since 2009 the EU ETS has experienced a growing surplus of allowances and international credits compared to emissions which has significantly weakened the price signal (European Commission, Climate Action, 2012).By early 2012 the surplus had reached 955 million allowances and a continued rapid build-up is expected over the rest of 2012 and in 2013 due largely to a number of temporary factors directly related to the transition to phase three (2013-2020) (European Commission, Climate Action, 2012).

There are now a variety of mechanisms for trading carbon emissions. The largest is the European Union Trading System (EU ETS), a cap and trade scheme that emerged out of the Kyoto Protocol. 6349 million metric tons of equivalents ($MMtCO_2e$) were traded in 2009 at the five most active exchanges in the EU ETS (Mizrach, 2012). For many, the ideal vehicle for funding the demonstration and subsequent plants would be the EU emissions trading scheme (EU ETS). However, almost all proponents of CCS agree that the EU ETS is not yet sufficient to finance CCS because carbon prices are not high or stable enough. Therefore other options are required- at least in the short to medium term (Scrase, 2009).

In its 2008 Impact Assessment, the European Commission (2008a) used a range of analytical tools to assess the costs and benefits (including potential positive externalities) of different policy options for CCS support. These options ranged from doing nothing, including CCS in the EU ETS, to various permutations of a CCS mandate, and finally, inclusion of CCS in EU ETS with a subsidy. In this later document, the Commission came down in favor of the option of inclusion of CCS within the EU ETS, and argues against a CCS mandate or subsidy, an apparent change of position from the 2007 statement. The results of economic modeling are the main reason for this change, but the conclusion relies upon the ability of the EU ETS to provide a sufficient strong economic incentive for CCS development (de Coninck et al., 2009). It may be some time though before the carbon price in the EU ETS is high or certain enough for investors to rely on it as a source of finance (Scrase, 2009). It is uncertain if the ETS alone is an adequate incentive to achieve commercial deployment of CCS by 2025. Currently ETS-prices are considered too low and too volatile to trigger full-scale deployment (it is uncertain if the ETS alone is an adequate incentive to achieve commercial deployment of CCS by 2025), thus CCS should 'market-conform', with help of the ETS: CO_2 emissions reduction should generate 'credits' and thus funding for CCS investments (Vergragt, 2009).

The ACCSEPT survey findings lead to a few possible recommendations for policy makers at the European and national scales. Firstly, there is a strong support from all stakeholders in all countries for stronger incentives to support the further development and implementation of CCS within the EU. Most important amongst these are an early commitment to extend the EU ETS beyond the Kyoto reporting period with stronger national emissions caps.

5.1.10 Management of risks/externalities

According to de Coninck et al., "the risks of CCS are difficult to define and identify, not just technically, but in terms of the way different people and organizations understand and interpret risks. The basic conclusion of an examination of potential risks is that, because the risks from climate change due to fossil fuel emissions are larger and far more difficult to manage than the risks of CCS, the risk of leakage from storage should not impede CCS development overall"(de Coninck et al., 2009). One of the key uncertainties about CCS is whether the storage of CO_2 is safe. The risk of storage is associated with local environmental, health and safety risks and the risk carbon dioxide leakage, re-entering the atmosphere, thus undermining the emission reduction targets and climate change goals. There is uncertainty about probabilities and risks and a lack of experience with geological storage by developers, regulators and researchers. These risks vary across storage options and settings (Markusson et al., 2010). Much of the difficulty in regulating CCS however lies in the site-specific nature of CO_2 storage and associated risks. Hence diverse levels of analysis and action are needed, which will require further capacity building and coordination (de Coninck et al., 2009). The already identified major risks incurred by CCS should be guiding the initial decisions about site location and exploitation and ongoing monitoring and evaluation should be robust enough to draw further conclusions (de Coninck et al., 2009).

CCS has also externalities which have negative impacts arising from increased coal extraction, increased sludge production from this and from the capture progress itself, increased water usage and completely new emissions from chemical scrubbers where post-combustion CO_2 takes place (Rubin et al., 2007). Furthermore, risks associated with CO_2 pipeline infrastructure and potential conflicts with other users of geological storage reservoirs. The nature and cost of these externalities are not currently well understood and more research is therefore needed. In the ACSSPEP survey, the stakeholders' perceptions about CCS show that the issues which are identified as being highest risk are: (a) additional fossil fuel use because of the energy penalty, (b) human health and safety from onshore CO_2 storage and (c) environmental damage from both onshore and offshore CO_2 storage. The lowest levels of perceived risk are associated with accidents arising from inclusion of CO_2 capture at power stations and human health and safety risks from offshore CO_2 storage site leakage. The sample as a whole did not consider the risks of CCS to be particularly large. The most common response for all the risks assessed is 'minimal risk'. 'Very serious' risk never appears as a prominent response for the sample as a whole with respect to any of the risks.

Developing appropriate (e.g. credible and long term) risk governance mechanisms is therefore essential for the deployment of CCS to be successful (Markusson et al., 2010). Whilst risks from CCS are often presented as technical risks posed by introducing CO_2 into new environmental content, it may well be that management decisions about storage are as important as, if not more important than, physical risks (de Coninck et al., 2009).

5.1.11 Dependency on fossil fuel

The growing global demand for energy services makes it improbable that the large quantity of energy stored underground in fossil fuels will remain unexploited. CCS is increasingly discussed as a potential means to prevent the release into the atmosphere of the carbon in those fuels (Sathre et al., 2012). It has been widely assumed that coal, unlike oil and gas, will be abundant for at least another century. A recent estimate by the US department of Energy of coal resource life time is 164 years at the current production rate (USDOE, 2007a). Another estimate is that coal has a resource life of 133 years at current production rates, i.e. a resource life of 133 years (BP, 2007). This compares to estimated reserves of oil and gas which are expected to last for 42-60 years respectively at current rates of consumption (BP, 2007). If the potential increase in coal consumption is taken into account, then the coal resource life decreases (de Coninck et al., 2009). The USDOE considers that coal consumption might increase by 77% between 2005 and 2030, which would reduce the resource life globally to about 70 years (USDOE, 2007a). It would appear that the historical abundance of coal, which has typically been believed to last up to ten of generations of human lifespan, has prevented serious efforts in reliable accounting of its long term availability (de Coninck et al., 2009).

Obviously coal power plants have lower direct investment costs than gas power plants or other alternatives. However, many studies have mentioned the high indirect costs, the high emissions, the accidents and environmental burden of coal mining, and others (Vergragt, 2009). Recent studies confirm that when the external costs (especially CO_2 emissions) are included, natural gas has the lowest costs, while coal power plants have the highest (Sevenster et al, 2007). Both IEA and EIA implied that fossil fuels are likely to continue to act as the main source of CO_2 emissions before 2030. Thus, carbon capture and storage (CCS), by which CO_2 is captured when generating power and injected underground for storage, is suggested by UK Department of Trade and Industry (DTI) as ' the most promising way to stabilize greenhouse gas content in the atmosphere' (DTI, 2003). In order to limit climate change it has been estimated that CO_2 reductions of between 60% and 80% in 2050, compared to 1990, are required for industrialized countries such as those of the EU. Current trends and projections show an increase use of coal in the EU over the coming decades. If climate change policy objectives are to be met concurrently with coal and gas remaining an important part of the fuel mix for European electricity generation, then the implementation of CCS will be necessary in the EU (Vergragt, 2009). However, a new coal-fired power plant has a design life of approximately 20-40 years. If CCS were not to be implemented in any serious way until 2020, however, then it may well be the case that only one generation of power plants is constructed due to the depletion of coal supplies (de Coninck et al., 2009).

According to Vergragt, 2009:17, "fossil fuel lock-in would mean that it would become eventually even more difficult to move away from fossil fuels to renewable and conservation. All institutions which now invest in CCS, either monetary or by creating regimes for regulation and monitoring, will have vested interests to continue this system to remain functioning in the far future. Even in the best case scenario, when investments in CCS would be based on a massive scale till at least 2080. Beyond that date monitoring and safeguarding of CO_2 storage will remain necessary for an unforeseeable time, even if businesses and politics would move away from CCS between 2040-2080"(Vergragt, 2009). The uncertainty surrounding coal supplies does not imply that CCS should not be implemented, however, because many hundreds of coal-fired power plants will likely be constructed worldwide over the next several decades, and CCS can be deployed progressively and more efficiently with the build-up of know-how(de Coninck, et al., 2009).

5.1.12 Need for stronger Incentive mechanisms

According to the findings of the ACCSEPT survey, there is clearly strong support from all stakeholders in all countries for stronger incentives to support the further development and implementation of CCS within the EU. Currently EU ETS prices are considered too low and too volatile to trigger full-scale development thus Rotterdam Climate Initiative believes that additional incentives, such as an emission performance standard (a CO_2 norm per produced kWh), are needed to ensure the successful implementation of CCS. The government should focus its incentives measures mainly on the capture and storage aspects of the value chain. A large-scale investment programme, associated with the participant/ owner role is considered undesirable (Schokkenbroek et al., 2011). Similarly in the UK, an alternative approach to public funding would be to focus on performance incentives. This could arguably encourage companies to minimize risks so that they can maximize their revenue-and, in the case of CCS, the carbon emissions reductions (Scrase, Watson, 2009).

In 2007 the European Commission had noted that it: "believes that by 2020 all new coal-fired plants should be built with CCS" (European Commission, 2007a, p.10). it argued that "a clear and predictable long-term framework is necessary to facilitate a smooth and rapid transition to a CCS-equipped power generation from coal" (European Commission, 2007a) and explored three possible incentives: a) establishing a more favorable long-term investment framework by "ensuring the relative perpetuity of the emissions trading scheme and by facilitating and risk-sharing instruments" (European Commission, 2007a, p.10). b) Developing EU CO_2 storage sites and pipelines for multi-user access or projects for CO_2 infrastructure development at Member State level. c) "adopting legally binding measures to regulate maximum allowed CO_2 emissions per kWh after 2020 and/or introduce a time phase-out (for instance by 2050) of all high CO_2 emitting (i.e. non-CCS) electricity generation" (European Commission, 2007a, p.10). Possible incentive mechanisms mentioned by the Commission include: privileged access to the electricity pool for zero-emissions power; high buy-back prices for 'sustainable electricity"; and/or timed phase-out of high CO_2-emitting installations (de Coninck et al., 2009).

The stakeholders' perceptions about what are the most appropriate incentives for CCS development in home countries in the ACCSEPT survey are as follow: By far the most popular option is for Research, Development& Demonstration (RD&D) with over 90% of respondents in favor. This is followed by early commitment to extend the EU ETS with tighter emissions caps. The third most popular option is a requirement for electricity generators to supply a given percentage of zero- or low-carbon electricity but without specifying the source of electricity (i.e. it could be from

CCS but also from renewables or nuclear. The next three most popular options in descending order are: i)an economy-wide carbon tax; ii)a capital subsidy scheme to support construction of CCS plant and iii) a requirement for electricity generators to supply a given percentage of zero- or low-carbon electricity produced by CCS (ACSSEPT, 2007).

5.1.13 Reliable estimations on storage capacity

The most important factors influencing the development of CCS are availability of suitable geological storage sites and price of carbon under the EU Emissions Trading Scheme (ACSSEPT, 2007). There are numerous sedimentary basins and geological reservoirs within the EU that are judged suitable for CO_2 storage. The major, suitable off-shore sedimentary basins are located in: the North Sea, the Hebrides, the Norwegian Sea, the Baltic Sea, the Mediterranean Sea and off the Iberian Peninsula (de Coninck et al., 2009). The major on-shore sedimentary basis are located in or below : Denmark, the North German Plain, Hungary, the Carpathians, Molasse, Paris, SE and parts of northern England, Belgium, the Apennines (Italy), Sicily, SW France and Spain. The Zero Emission Power Plant Platform (ZEP) estimates that the Utsira formation in the Norwegian sector of the North Sea could be used for the storage of 2 billion tones of CO_2 each year (ZEP,2006), which is probably enough storage capacity for the foreseeable CCS projects in the EU for at least the next 20-30 years. The EU commission quotes IEA estimates that the Norwegian sector of the Utsira formation is capable of storing up to 600 billion tones of CO_2 and that this would allow storage of all of the EU's emissions (at current levels) for over 300 years (European Commission, 2007a). Questions have been raised regarding the accuracy of these estimates, however, the problem being that there is no agreed methodology for calculating the storage capacity of saline aquifers for CO_2 storage (Holloway et al., 2006a,b; Bachu et al., 2007; Bradshaw et al., 2007).

The preparations for the introduction of CO_2 capture, transport and storage (CCS) on an industrial scale have been under way for several years now. As a first step, the storage capacity for CO_2 hydrocarbon fields and aquifers has been established or estimated in many countries around the world (Neele et al., 2011). If storage capacity is not available in time this could seriously delay the implementation of CCS. On the basis of efficiency considerations (such as the existing knowledge of geological and reservoir models, costs, safety) it may be preferable to enable current gas-field operators to become CO_2 storage operators. This would facilitate transition (Schokkenbroek et al., 2011).

In the Netherlands the offshore gas fields provide a storage capacity of about 1 Gt, which will become available over the next few decades. Existing production facilities may be re-used for injection. Uncertainties in storage capacity, injection rates and time of availability require an analysis of the feasibility of storing CO_2 at the rates currently projected for the period 2015-2050 (Neele et al., 2011). Neele et al., 2011 came to the following results: a) storage will be limited by injection rate limitations by about 2050, when 70-75% of the storage capacity is used. By this time alternatives need to be available b) capture installations built before in the Rotterdam and Amsterdam regions 2050 will produce more CO_2 during their economic lifetime (assumed 40 years) than can be stored offshore, due to limitations in both injections rates and storage capacity. These results indicate the careful planning of offshore CCS is required to optimize the development of CCS. Planning (field strategy) will help to follow the most cost-effective route, to exploit the capacity available in offshore gas fields (both injection rates and storage capacity) and to make available alternative locations in time (Neele et al., 2011).

In conclusion, whilst there are certainly abundant potential reservoirs for CO_2 storage, at this stage it is difficult to provide reliable estimates of CO_2 storage capacities in European reservoirs (de Coninck et al., 2009). The European Commission's Impact Assessment (2008b) included an analysis of CO_2 sources and geological reservoirs that there was sufficient storage capacity to 2030. Claims that all of the European Union's CO_2 emissions for the next several hundred years could be stored in saline aquifers cannot, at the current time, be justified and could give a misleading impression to policy makers (de Coninck et al., 2009).

2.1.14 Insufficient CO_2 price

The paper of Daskalakis, Psychoyios, MAarkellos, 2009, studied the three main markets for emission allowances under the EU ETS, Powernext, Nord Pool and ECX. The empirical analysis indicated that emission allowance spot prices are likely to be characterized by jumps and non-stationarity. The high volatility and the existence of extreme discontinuous variations in carbon prices mean that much caution is needed when dealing with emission allowance derivatives. When the first external verified reports regarding each EU member state's actual emissions during the previous compliance year came out in April 2006, prices soared up to their maximum level of nearly 30 Euros (Daskalakis et al., 2009). Soon after, market participants realized that the EU member states had over allocated allowances to their emission intensive firms and that the market was not as short as was thought to be. Combining this with the banking prohibition from 2007 to 2008 resulted to a market correction that wiped out over half of the EU ETS market value. Specifically, spot prices dropped abruptly to less than 10 Euros per EUA. As a result, the spot markets under scrutiny are characterized by a very high historical volatility.

The total costs for capture, transport and storage are thus calculated in the range of 25-27€/ton, with the largest uncertainty in the capture (Vergragt, 2009). This is the same range as the estimates by the European Commission, which estimates that the price of emission rights from the ETS should be in the order of 39-45€/ton in order to jumpstart CCS. (Vergragt, 2009). In the assessment of the 'Schoon en Zuinig' program by ECN (Energy Centre Netherlands), the Dutch ambitions are called ambitious and probably not achievable because too much is dependent on developments elsewhere in Europe and the developments of the CO_2 price on the market

(ECN,2008). In the ‘low’ EU scenario, with moderate EU policies and modest CO_2 prices of 20€/ton CO_2, it is remarkable that there will be hardly a contribution by CCS in the Netherlands in 2020 (Vergragt , 2009). In Finland, the most important driver for utilization of CCS is the development of the price for emission allowances in the ETS (Teir et al., 2011). In the UK, for many, the ideal vehicle for funding the demonstration and subsequent CCS plants would be the EU ETS. However, almost all proponents of CCS agree that the EU ETS is not yet sufficient to finance CCS because carbon prices are not high or stable enough (Scrase, Watson, 2009). It is uncertain if the ETS alone is an adequate incentive to achieve commercial deployment of CCS by 2025. Currently ETS-prices are considered too low and too volatile to trigger full-scale deployment (Rotterdam Climate Initiative).

CCS is costly, energy intensive and needs to be carefully developed and implemented. A necessary condition is that CCS will become part of the ETS carbon system in 2012, with a stable (and possibly guaranteed) price for CO_2 of about EU 45 on the market (Vergragt, 2009).

5.1.15 Other barriers

Amongst the barriers for the deployment of CCS technology in order to reduce the CO_2 emissions and reach the targets of the Kyoto Protocol stand the coal tax and the international common level playing field. Apart from the carbon prices which are currently too low and too volatile to trigger the full-scale development, an additional incentive would be the international level playing field. According to Rotterdam Climate Initiative “a (international) level playing field will have to be maintained. RCI is actively involved in talks with national emitters and in-round table discussions with the major players on the Northwest European electricity market to look into possible ways of accelerating the implementation of CCS”. As for the coal tax is concerned, in the ACCSEPT EU-funded survey, the economy-wide carbon tax stands in the fifth position amongst other financial incentives, according to stakeholders’ perceptions of CCS in Europe. Energy stakeholders are, overall, in favor of an economy-wide carbon tax, but there is a sizeable minority against, as there is also amongst parliamentarians. All stakeholder groups appear to support an early commitment to extend the EU ETS with tighter emission caps (ACCSEPT, 2007).

5.2. Inter-linkages between barriers

After having identified the barriers for the full-scale deployment of CCS technology, it is essential to look at inter-linkages between those barriers, since this can provide with important information about synergies and trade-offs between the barriers the public and private decision makers on CCS. Certain efforts to reduce or manage a certain barrier by policy makers can have effects on other barriers. The political and regulatory framework on CCS, carbon prices, carbon reduction goals and inclusion of CCS in the EU ETS, etc., will affect the economic and financial viability of the deployment of CCS. Public acceptability on storage and public confidence in stakeholders are affected by the information availability on CCS and on CCS cost improvements and at the same time they are necessary for political support and impacts on policy and regulatory decisions. Uncertainty about the costs of CCS raises difficulties for policy makers to create the appropriate regulatory framework in order to mitigate the climate change and this becomes more complicated when comparing to other mitigation options, for instance Renewable Energy. Learning by doing can help reduce costs thus stimulating investments and learning. Different governance and business models may impact on the speed and viability of development and up-scaling. A top-down push may increase speed, but also increase risks of technology failure (Markusson et al., 2010). Different business models for handling financial risks may fit best with different ways of integrating CCS systems. Learning how to integrate and coordinate CCS systems may be costly (Markusson et al., 2010). Finally a common level playing field and a strong top-down coordination of the CCS community can facilitate consensus about technology options and reduce the risk of carbon lock-in.

Summary

In this chapter there was a description of the barriers and uncertainties for the full scale deployment of CCS, which were identified from existing social science literature on CCS so as to establish what is already known from a social science point of view and identify gaps regarding technical, economic, financial, political and societal aspects of CCS. The barriers and uncertainties are the lack of robust-transparent legal framework, the economic and financial viability, the carbon lock-in, the gaps in knowledge, the variety of CCS pathways, the carbon leakage to non-ETS countries, the renewable energy competition, the public acceptance-resistance, the inclusion of CCS in ETS, the management of risks and externalities, the dependency on fossil fuel, the need for stronger incentive mechanisms, the reliable estimations on storage capacity, the insufficient CO_2 price and other barriers (level playing field/coal tax). The inter-linkages between the barriers and uncertainties were also presented, which can provide with important information about synergies and trade-offs between the barriers the public and private decision makers on CCS. In the next chapter an overview of the evaluation criteria (barriers and uncertainties) for the full scale deployment of CCS regarding the three scenarios created is following, as well as the findings from the interviews with experts conducted.

CHAPTER 6

RESULTS

This is an overview of the evaluation criteria (barriers and uncertainties) for the full scale deployment of CCS regarding the three scenarios created, a short term, a medium term and a long term, according to the experts who were interviewed. The persons interviewed were three academics, three from the business sector, one from the governmental sector and one expert from an environmental group. Apart from the assessment of the barriers and uncertainties identified by the writer, there is also a description of additional barriers which were proved to be important by the experts interviewed, how the feasibility of CCS deployment is perceived by the experts, the differences between experts in how they perceive the barriers and differences in how CCS is perceived in different countries globally. There is also a description of how the most important barriers and uncertainties can be overcome, according to the experts' point of view.

6.1 Short-term, medium-term and long-term assessment of full scale deployment of CCS

A presentation of the barriers and uncertainties as factors in assessing CCS technology and the possibility of its full scale deployment and their explanations follows. The scores used for assessing the barriers and uncertainties are shown in figure 7**.** Based on the ex-ante expectation of the writer that the expertise of the experts interviewed is similar regarding CCS technology and the associated barriers for its full scale deployment, there was no weight application on the barriers during the scoring process.

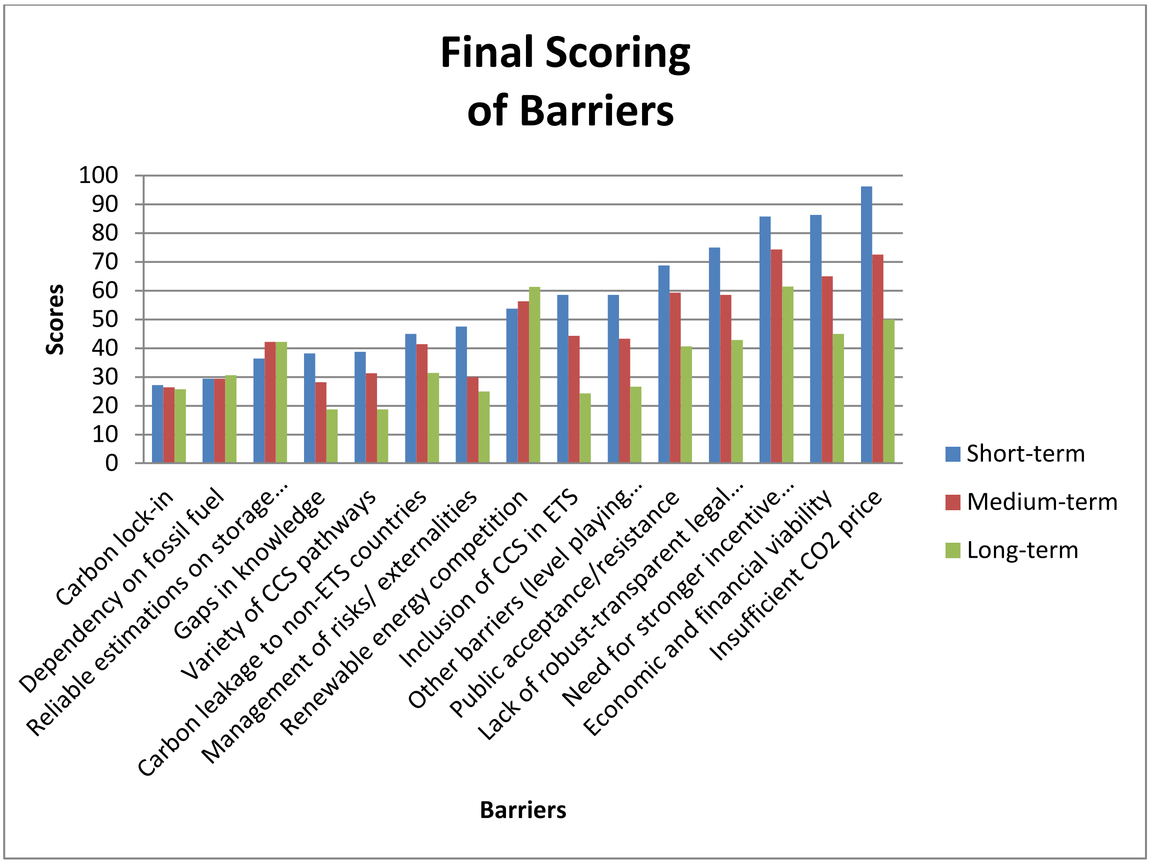

figure 7 **Final scoring of the barriers**

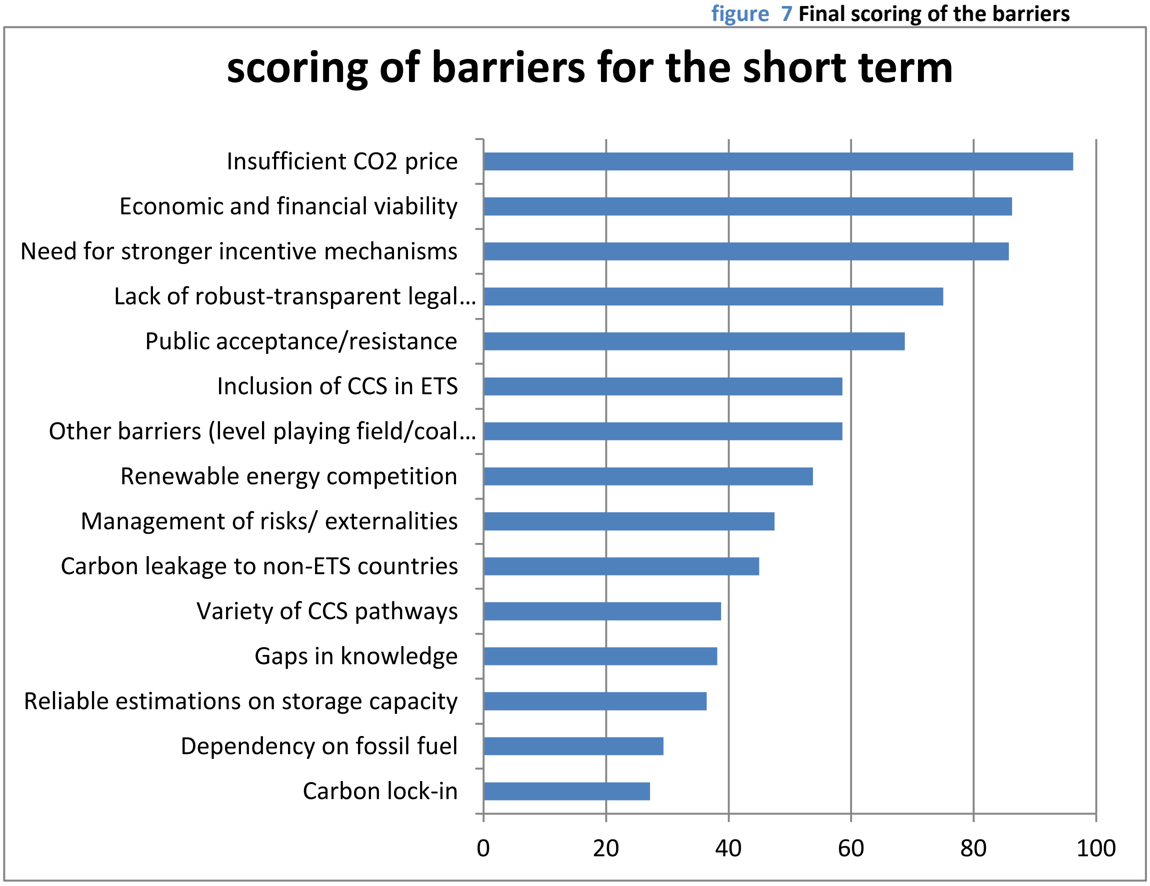

figure. 8 Scoring of barriers for the short term

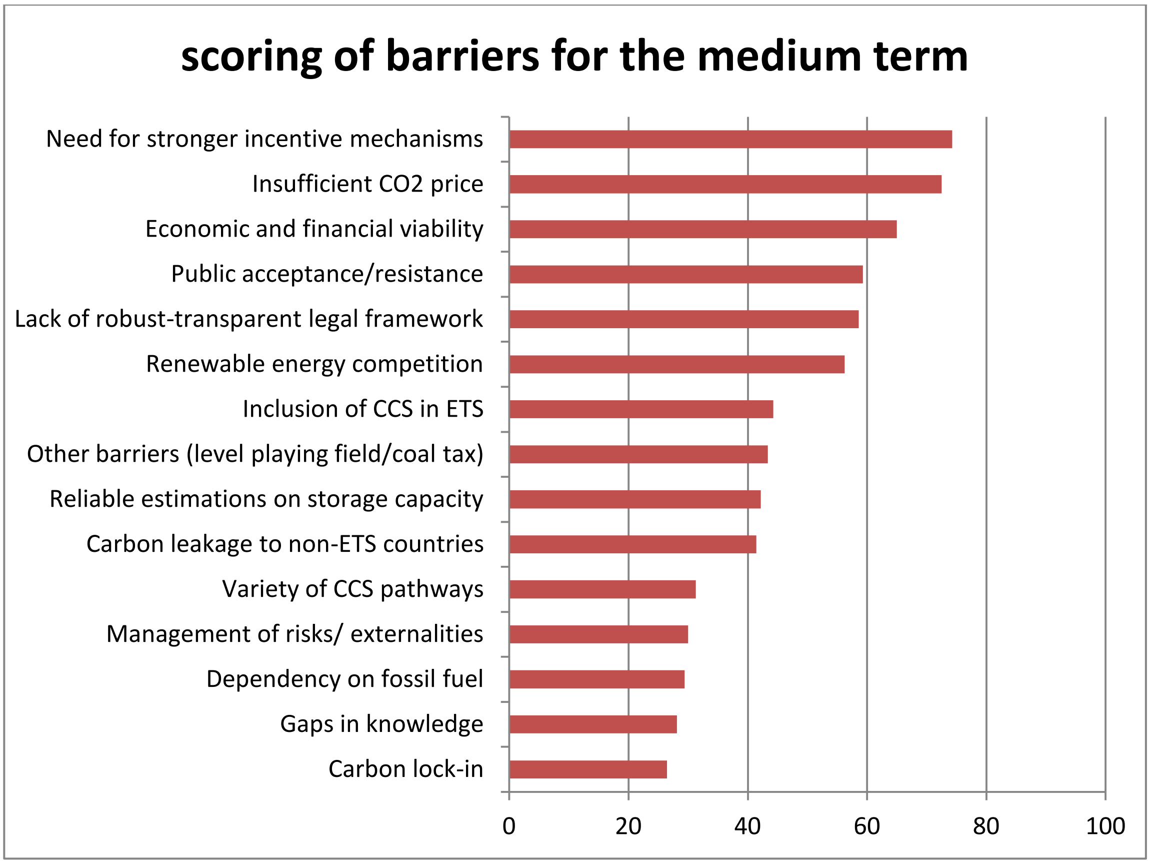

figure. 9 Scoring of barriers for the medium term

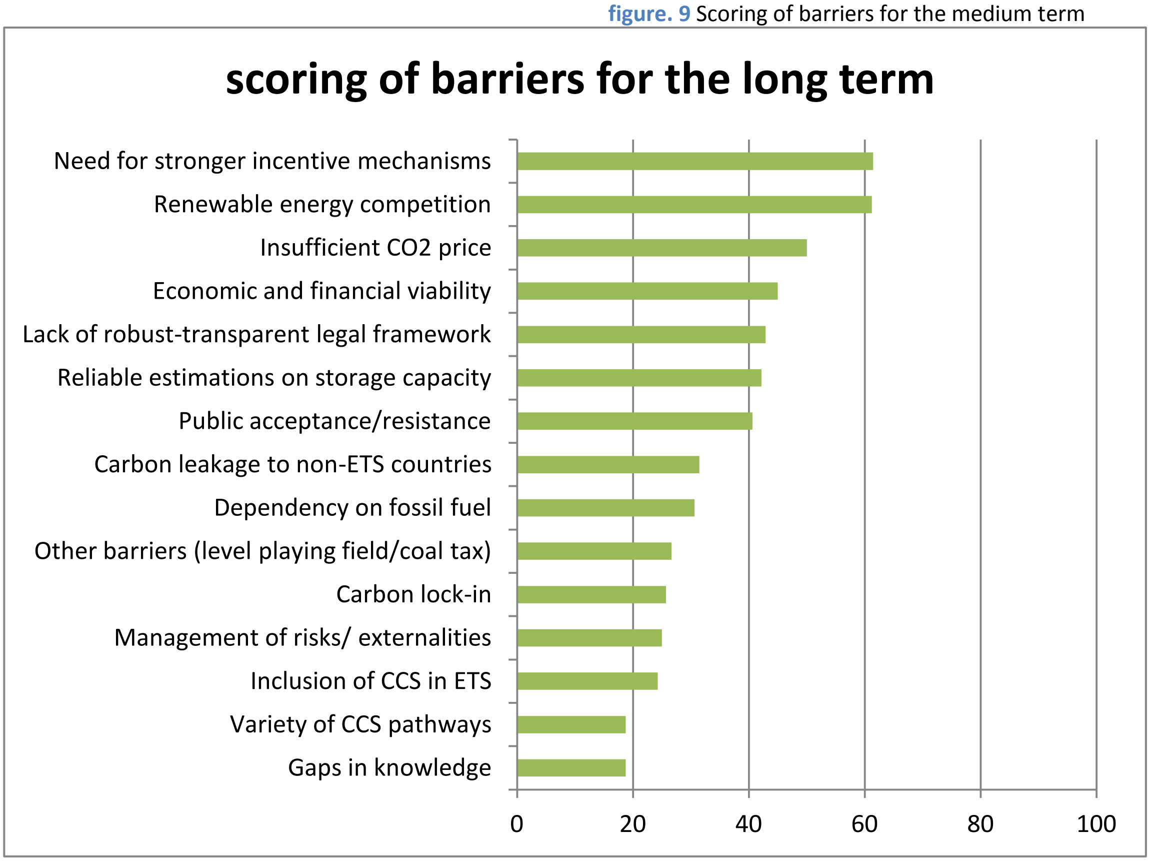

figure. 10 Scoring of barriers for the long term

Lack of Robust-transparent legal framework: In the short-term scenario the lack of robust and transparent legal framework is a crucial barrier for the full scale deployment of CCS, since there is still a lot of work to be done on this field. The legal framework is seen as a stable uncertainty and as a result of policy and will remain a barrier if there will be no consistent policies. It is also seen as an important uncertainty from the perspective of the operators of CCS. If there will be not a consistent policy by 2020, the lack of robust and transparent legal framework will become a serious problem for CCS. According to the opinion of expert A of the business sector and the expert of the governmental sector this will remain the same both in the medium and the long term, while for the rest of the participants it is expected to decrease in the medium and long term respectively.

The lack of robust-transparent legal framework is the fourth most important barrier to overcome for the full scale deployment of CCS in the short term, in the medium term decreases to fifth position while in the long term remains in the fifth position.

Economic and financial viability: In the short-term scenario the economic and financial viability of CCS is a very important barrier for the full scale deployment of CCS, for the reason that there is uncertainty for the ETS prices, its dependency on subsidies and the fact that CCS is very energy intensive. From the business sector, expert A estimates that the economic and financial viability will remain stable and of the same importance for the medium and long term scenarios, while for the second expert it is the most important barrier. As for the rest of the participants, it is expected to shortly decrease in the medium and long term because of the improvements in technology and the economic positioning. However, academic B estimates that CCS will remain an expensive technology in the future.

The economic and financial viability is the second most important barrier to overcome for the full scale deployment of CCS in the short term, while for the medium term becomes the third most important and for the long term the fourth.

Carbon lock-in: for the criterion of carbon lock-in there were significant differences in experts' opinion, varying from not at all important to very important. For the expert of the environmental group, carbon lock-in is an important barrier since CCS has a very close and tight relation to coal power plants, which relation does not lead to the real transition to sustainability, low carbon emissions, circular economy and renewables. From the perspective of the business sector, carbon lock-in is only seen as a barrier from the NGOs, because of the public opinion which is formed by the NGOs. For the business sector and academic C, It is more an incentive for CCS than a barrier, since energy demand will grow significantly and coal power plants cannot be avoided, thus carbon lock-in is an incentive. For the experts who believe that carbon lock-in is not a barrier for the full scale deployment of CCS, the explanations vary: for academic B it is not a barrier because the new factories are already built with CCS capabilities, while for academic A it is not a barrier because CCS will not become widely applied. Additionally carbon lock-in is seen as not a barrier for the expert of governmental sector because Europe will become self sufficient in energy supplies and independent on oil and gas. In the medium and long term the importance of carbon lock-in is expected to decrease by the experts. Only expert A from the business sector considers that carbon lock-in will become more relevant in the medium term, while in the long term carbon lock-in will be an important issue. Similarly, the expert of the environmental group considers that carbon lock-in will remain of the same high importance in the medium and long term, unless if CCS becomes more related to sustainability and low carbon economy by the use of CO_2 in agricultural activities, CO_2 re-use and disconnected to coal power energy production.

The carbon lock-in is the least most important criterion for the full-scale deployment of CCS in the short and medium term, while for the long term becomes 11th out of 15.

Gaps in knowledge: for almost all of the experts the gaps of knowledge is not an important barrier for the full scale deployment of CCS. Only for the academic A with the technical background it is not at all a barrier, since there is more than enough knowledge to scale up CCS. For academic C there are at the moment gaps in knowledge which will change in the future. For the expert B of the business sector there are gaps in knowledge in terms of reducing the costs and it will become of more importance in the future since R&D and deployment are essential in order to gain knowledge on how to decrease the costs. In general, it is considered that there is enough knowledge to start-up in the short term, although demonstration projects are still needed to give experience and additional knowledge. There can also a distinction be made, between knowledge related to onshore and offshore storage, because there are still gaps in knowledge for the storage under salt water layers and lakes. The gaps in knowledge on onshore storage are considered by the expert of the environmental group to be larger. In the medium term the gaps in knowledge are expected to decrease by all the experts apart from business sector B, who expects the gaps to increase also in the long term from the perspective of reducing the costs. In the long term the rest of the participants expect that there will be no more gaps, thus this will be not at all a barrier in the long term for the full scale deployment of CCS.

The gaps in knowledge in the short term are in the 11th position, while in the medium term in the 14th and in the long term in the last position (15th).

Variety of CCS pathways: for all of the experts, the variety of CCS pathways in not a very important barrier for the full scale deployment of CCS in the short term. For academic A, expert C from the business sector and expert from the governmental sector, the existing factories can only be post-combustion, which is a mature enough technology, while the oxy-fuel technology is still developing and can be an alternative technology in the future. For expert B of the business sector, the existence of different technologies is good, it becomes though more complicated on how to integrate and communicate the different technologies, which may also give a confusing picture to the governments. For some this is considered to be a motivation, while the expert of the environmental group claimed that there is not much research on other alternative techniques for more pure CO_2, air contamination and gasification and research is only towards one direction, thus being a barrier at the moment. In the medium and long term the variety of CCS pathways is expected to decrease for most of the experts. Contrary, two of the experts, business sector A and academic A expressed the possibility that the variety of CCS pathways can be a barrier in the medium term because of the increasing knowledge which may lead to new technologies, while in the long term it will not be a barrier.

The variety of CCS pathways is of less importance for the full scale deployment of CCS in the short and medium term (11th position) and becomes even of less importance for the long term (14th position).

Carbon leakage to non-ETS countries: carbon leakage to non-ETS countries was not considered as a barrier for the full scale deployment of CCS by the governmental sector expert regarding all of the three scenarios, short, medium and long term because the power sector cannot reallocate. As for the rest of the experts, in the short term, for academic B it is not a big issue since in Europe there is quite a good general understanding that the CO_2 emissions have to be addressed. It could though be a barrier for American companies. However, expert A from business sector said that it is still a barrier if CCS is not treated as a world scale solution to tackle climate change. If so, there can be an interest in non ETS countries. Similarly, expert B from the business sector finds the carbon leakage to non ETS countries a barrier for global industries, since there is a need for fair competition. The rest of the experts find that carbon leakage to non ETS countries is always a risk, depending on what the other continents will act regarding CCS. For some of the experts it is expected to decrease in the medium and long term, while for the rest it will remain an issue, since the price of energy will always be an important factor for companies on deciding whether to reallocate or not. For academic A the allocation is already happening in China. It will remain rather high, depending on the deployment of CCS in China. In the long term it is expected to decrease and on the other hand for the expert from the environmental group it may be an opportunity to attract companies specialized in energy sources and innovation.

The carbon leakage to non ETS countries is not an important barrier for the full scale deployment of CCS in the short and medium term (10th position), while in the long term raises in the 8th position.

Renewable energy Competition: almost all of the experts express the idea that CCS should not competing renewable energy sources. Instead, CCS should be considered as the necessary technology for the transition to sustainability, which will fill the gap between the present and future technologies. However, in terms of subsidies and funding there is a competition element, which is also encouraged by the politicians. In the short term, the competition is quite an important barrier for the full scale deployment of CCS in terms of funding, which is expected to increase in the medium and the long term for the reason why the renewables will improve, become better and cheaper and CCS may also remain a costly technology. Only the experts C and B from the business sector believe that the competition between CCS and renewables will decrease. Expert C believes so because CCS in the future will be self financed through the ETS and will not be dependent on subsidies anymore. Expert B believes that the competition will decrease for the reason why people will understand that a mix of everything will be needed. Furthermore, it was expressed by the expert of the environmental group that this competition does not help the renewables, it will be a crucial barrier if CCS will be still closely connected to the building of coal power plants. On the other hand, academic A considers that this competition is more likely to be a barrier for the deployment of renewables, rather than for the full scale deployment of CCS, since companies are already investing in CCS instead of RE. Finally, academic C considers that the lack of competition is a barrier for the full scale deployment of CCS and that there should be more competition.

The Renewable Energy competition in the short term is not an important barrier for the full scale deployment of CCS (8th position), while will become of more importance in the medium term (6th position) and will be the second (2nd) most important barrier in the long term.

Public acceptance/resistance: public acceptance and resistance is considered to be for most of the experts interviewed a very important barrier for the full scale deployment of CCS in the short term, especially when related to onshore storage of CO_2. Public resistance is higher onshore when related to offshore storage. For those experts it is expected to decrease in the medium and long term because the public will get used to the projects which will be done, most of the CO_2 storage will take place in offshore sites and if offshore storage will prove to be safe, then CCS will become accepted. In the long term there will not be public resistance at all. For the expert C of the business sector public resistance is expected to become a serious barrier for the full scale deployment of CCS in the medium term, because in the case of Rotterdam and Western Europe the captured CO_2 form Germany and Belgium has to be transferred to Rotterdam by onshore pipelining. As long as there is not experience and CCS is not proven to be safe, there will be public resistance, which in the long term will decrease. Academic A considers public resistance as a very important barrier for the deployment of CCS, which will remain the same in the future because people will never accept CCS (NUMBY). Similarly, public resistance will always be a barrier for onshore storage, according to the expert of the environmental group, for the reason that there is mistrust and misinformation on CCS, for instance the property values on onshore storage fields and the discussion between NGOs, scientists, companies and the public will always be difficult and hard to be objective. For the offshore storage however, public resistance is lower, not an important barrier and will decrease in the future. Academic C also believes that public acceptance is and will remain a crucial barrier, since at the moment people do not trust new techniques unless they are proven, in the medium term there will be resistance because of the transition to a green economy in which people will resist to old technologies based on CO_2 and fossil fuel and in the long term CCS will not become a safe technology and will belong to an old economy.

Public acceptance and resistance is the 5th most important barrier to overcome for the full scale deployment of CCS in the short term, becomes more important in the medium term (4th position) and in the long term becomes of less importance (7th position).

Inclusion of CCS in ETS: the expert from the governmental sector expressed that CCS in already included in ETS thus this is not a barrier for the full scale deployment. The academic A did not give an answer because the question was not relevant to his field of expertise. The rest of the experts said that the inclusion of CCS in ETS is a very crucial factor for the deployment on CCS in the short term. Currently, the ETS is not working properly and if continues doing so, there is no future for CCS. It is mainly to convince the private sector to move to investments although without CO_2 rights this is unlikely to happen. In the medium term this will remain critical for the deployment of CCS while in the long term it will not be barrier anymore, because CCS will be integrated in ETS and also CCS will be used for EOR. The expert B of the business sector though did not consider the inclusion of CCS in ETS as a barrier, for the reason that it is all about the price of CO_2 to become high.

The inclusion of CCS in ETS in the short term is the 6th more important barrier to overcome for the full scale deployment of CCS, while in the medium term becomes 7th and in the long term decreases to the 13th position.

Management of risks and externalities: for half of the experts interviewed the management of risks and externalities in the short term is an important barrier for the full scale deployment of CCS because at the moment there is not much experience. For some it is expected to decrease rapidly in the medium and long term because of the experience which will be gained in the future, while for the expert A of the business sector it will remain of the same importance in the medium and long term. The rest of the experts interviewed did not consider the management of risks and externalities as a barrier for the full scale deployment of CCS because there is good knowledge, modeling technologies and general understanding for the use of oil and gas fields. In the medium and long term it will not be a barrier at all. The expert B of the business sector considered that the management of risks and externalities is more relevant to the power companies which have less understanding of the risks and depend on operators.

The management of risks and externalities stands in the 9^{th} position for the short and medium term, while for the long term decreases in the 12^{th} position, regarding its importance for the full scale deployment of CCS.

Dependency on fossil fuel: for academics A, B, C, and experts B, C from business sector, the dependency on fossil fuel is not a barrier for the full scale deployment of CCS because there are enough fossil fuel for the next century so as to invest in CCS, the economic development for the next decades relies on fossil fuel, consequently CCS is becoming necessary and the people who deal with fossil fuel energy production are those who most advocate CCS. It is more of a motivation and incentive than of an argument for the deployment of CCS. On the other hand, the dependency of fossil fuel is seen as an uncertainty by the expert of the governmental sector, because there is still not enough knowledge of the future possibilities of fossil fuel, even though for the next century fossil fuel will be needed. According to the expert of the environmental group, the dependency on fossil fuel is not an incentive for CCS but a barrier and this dependency is part of the problem. For the expert of the governmental sector, the dependency will remain of the same high importance in the medium and long term, while for the expert A of the business sector it will become more of an issue in the medium and long term for the reason why the competition with RE will increase and CCS will remain dependent on fossil fuel, thus the dependency on fossil fuel will be an important issue in the long term.

The dependency on fossil fuel stands in the 14^{th} position in the short term, rises in the 13^{th} position in the medium term and becomes of more importance in the long term (9^{th} position).

Need for stronger incentive mechanisms: the expert C from the business sector considers the need for stronger incentives very crucial regarding the short term deployment of CCS because at the moment there are no incentives. His belief is that in the medium and short term this need will decrease because the costs of CCS are expected to decrease and there will be other than economic incentives necessary by that time. The expert B of the business sector considers the need for incentive mechanisms very important in the short term, while if there is economic and financial viability through the CO_2 price, there will be no need for extra incentive mechanisms. The expert A of the business sector considers that at the moment it is very important, which will become less important in the future because the costs of CCS will decrease. For the expert of the governmental sector in the short term it is not that important because the CCS community is still at the learning stage, but the need for incentives will increase in the medium and long term, for instance incentives like ETS or mandatory issues. For academic B and the expert of environmental group, the need for stronger incentive mechanisms is very crucial for CCS and will remain crucial in the medium and long term because it is mainly a financial barrier which will be overcome by subsidies, the competition with alternatives will increase because they will become better and cheaper and CCS is costly, energy intensive and there must be stronger permit demands. The academic C considers that it is important and will not change fast in the future. Finally, the academic A with the technical background did not score this certain barrier because it was not felt to be in the field of expertise.

The need for stronger incentive mechanisms is the 3rd most important barrier for the full scale deployment of CCS in the short term, while in the medium and long term becomes the most important barrier (1st position).

Reliable estimations for storage capacity: for the expert of the governmental sector and the experts A, C of the business sector, the reliable estimations on storage capacity is not a barrier for the full scale deployment of CCS in the short term because for the next ten years there is more than enough storage capacity. The estimations for storage capacity will become more relevant in the medium and short term if CCS will become a developed technology and if the demand for CO_2 storage will increase. In that case, the reliable estimations on storage capacity may become crucial. It is also depending on the timeframe of the transition to renewables. For the expert of environmental group and academic C this is more relevant in the short term and will decrease in the future because of research while for academic A with the technical background this is not at all an uncertainty because there is enough storage capacity, even if it is not considered to be efficient. Finally, the academic B did not score this uncertainty because it was not in the field of expertise.

The reliable estimations on storage capacity are not a barrier for the full scale deployment in the short term (13th position), while become more important in the medium term (9th position) and even more important in the long term (6th position).

Insufficient CO_2 price: the current insufficient price of CO_2 was considered as a very crucial element in whole discussion if CCS by all of the experts interviewed. The price of CO_2 is dependent on ETS and the problem is related to the instability of prices, which reflects the inability of politicians to create consistent policy and a robust and transparent legal framework. If the market for CO_2 starts working, then the price of CO_2 will increase. If EU continues the ETS system there will be real shortage in CO_2 permits. Moreover, CCS technology at the moment is not advanced enough and the processes of capturing and injecting are not clean, which will be overcome in the future because of the advances in the technology and the reductions in costs. A high CO_2 price would also mean the economic and financial viability of CCS. In the medium term the CO_2 price is expected to increase to 30-60 €/ton, which is sufficient for demonstration projects. All of the experts believe that in the medium and long term the price of CO_2 will increase, thus it will not be a crucial barrier for the full scale deployment of CCS, as compared to the short-term. It is only the expert A from business sector who believes that it will remain crucial in the medium and the long term as well, while expert C from business sector believes that in the end it will not be a barrier at all because of the transition to the renewable energy.

The insufficient CO_2 price is the most important barrier for the full scale deployment of CCS in the short term, in the medium term is the second more important (2nd position) and in the long term the third most important (3rd position).

Other barriers: the need for level playing field is considered to be very important by expert A from the business sector and will remain important the same for the full scale deployment of CCS in the future. Similarly the European level playing field was considered to be of major importance by academic B and expert from environmental group in the short term. For expert B from business sector the common level playing field is of high importance because all subsidies from EU now go to RE, which is not fair. For academic C it is of less importance while for the expert of governmental sector was not considered important. Finally, academic A did not give a relative score because it was not felt in the field of expertise.

The other barriers (level playing field, coal tax) are of moderate importance for the full scale deployment of CCS. In the short term stand in the 7th position, in the medium term in the 8th position and finally in the long term in the 10th.

6.2 Additional barriers and uncertainties

The participants were also given the opportunity to suggest additional barriers and uncertainties, which they considered as important, regarding the full scale deployment of CCS in the short, medium and long term. The additional barriers and uncertainties proposed are detailed below:

Political urgency of climate change: the sense of urgency in the political domain is a barrier for the full scale deployment of CCS. Is CCS urgent or not for Europe? It is the urgency and the public sense that affect the CO_2 price. CCS in the short term will not even start if the political domain does not see it as crucial. It will remain a crucial barrier in the medium term because the transition from pilot scale to full scale is needed and in the long term will be of less importance since CCS will be already commercial. The lack of a robust and transparent legal framework reflects the political urgency of climate change. If there is not urgency in the political domain, then this urgency will become the most crucial barrier for the full scale deployment of CCS.

Willingness to pay more for our energy supplies: the whole idea is based on creating a market for CO_2 but the society is not yet willing to put a price on CO_2 and pay more for the energy supplies because of its unawareness for climate change. The awareness of the climate change problem, its impacts and the possible solutions is the most important incentive, for instance extreme phenomena which will activate people more and make them consider CO_2 and its impact on climate change as more important. As a result, people will evaluate it higher and become willing to pay more for energy supplies.

Lack of infrastructure: the lack of infrastructure is considered to be a barrier for the full scale deployment of CCS. Investments in infrastructure are necessary for the scale up of CCS. Pipelines must be seen as a mean of transport and not as infrastructure and in order to invest in transport there must be a market. If there a market for CO_2 then there will be customers and investments in transportation of CO_2 will only be made if there are customers for the product.

Efficiency of CO_2 *capturing process:* the efficiency of CO_2 capturing process is considered to be a very important barrier to overcome, regarding the full scale deployment of CCS, for the reason why the process is very energy intensive. It is also a matter of innovation in how to use less energy in the process and since the present techniques are very energy intensive, innovation is needed.

Unawareness of climate change by the public: it is the lack of awareness by the public of climate change, of the role that greenhouse gas emissions (GHG) play in it, also the skepticism about GHG emissions and the impacts of climate change in the environment. It is a matter of awareness that climate change is a global problem and the possible ways to tackle down GHG emissions so as to prevent climate change.

Lack of global framework: the lack of global framework is a barrier for the full scale deployment of CCS, since there is a need for fair competition amongst the key players, which would also prevent carbon leakage to non-ETS countries, need for common reduction policies and need for global agreements. Europe has to feel that is not alone in the prevention of climate change. Additionally, there is need for collaboration between countries across Europe.

Differences in views between stakeholders:. The need for agreement between the stakeholders is urgent for the short term.

6.3 Feasibility of CCS full scale deployment

The stakeholders interviewed where also asked to identify the feasibility of full scale deployment, regarding the three scenarios created, a short term (2013-2020), a medium term (2020-2030) and a long term one (2030-beyond). There was also a fourth scenario created, which was that CCS will remain in pilot project level. The answers are shown in the table below:

	minimum feasible	less feasible	neutral	more feasible	maximum feasible
full scale deployment 2013-2020	5	3			
full scale deployment 2020-2030		4	1	3	
full scale deployment 2030-beyond		2	1	3	2
CCS remains in pilot project level	3	1	1	1	2

table. 2 Feasibility of CCS full-scale deployment

Five of the experts, business sector A, B, C, governmental sector and academic C find that the full scale deployment of CCS by 2020 is minimum feasible, while academics A, B and the expert of the environmental group find it less feasible.

As for the feasibility of full scale deployment in the medium term, it is considered as less feasible by academics A, C and experts form business sector B, C. For academic B is neutral while for business sector A, governmental sector and environmental sector is more feasible.

In the long term scenario, the feasibility for full scale deployment of CCS is less for academics A, C, neutral for business sector C, more for academic B, environmental group and business sector B. finally it is considered maximum feasible for experts A from the business sector and the expert from the governmental sector.

6.4 How to overcome the most important barriers

After scoring and identifying additional barriers and uncertainties related to the full scale deployment of CCD, the experts interviewed were asked to state their opinion on how to overcome the barriers and uncertainties which were considered to be as more important. A brief presentation of these barriers follows.

Economic and financial viability: the barrier of economic and financial viability for the full scale deployment of CCS can be overcome by the proper function of the ETS. At the moment the ETS is not working properly, also because the emission ceiling is high. A reduction in caps will put pressure on the industry. If ETS would work as it is supposed to do, then CCS could be viable and become commercial. Moreover there must be research on other possibilities of CO_2 usage, for instance in chemical products, EOR, agriculture activities and re-use of CO_2. The possibilities of different uses of CO_2 can make CCS more attractive to investments, thus making it economically viable. The flexibility of different uses and the existence of an interdependent system which can provide exchange of CO_2 between different locations and destinations can contribute to the economic and financial viability of CCS.

Insufficient CO_2 price: one of the most important barriers for the full scale deployment of CCS is the current insufficient CO_2 price. Without a sufficient CO_2 price there cannot be a market for CO_2 which will result in not existence of CCS. It is a matter of how ETS is working and to overcome this barrier ETS should be working properly. It is the political willingness, the political agreement and the collaboration between key players which have to convince the society that there is need for more consistent and tough energy policies. Furthermore, CCS can become full scale deployed by mandatory issues, such as the sewer systems in the cities.

Need for stronger incentive mechanisms: it is again a matter of politicians and their willingness to come into agreements with the key players so as to become with stronger incentive mechanisms for the full scale deployment of CCS and convince the society that there is need for more consistent and tough energy policies.

Public acceptance: in order to overcome the barrier of public acceptance and resistance the politicians have to involve the public into the discussion and show the interdependency between CO_2 and climate change and the options available to address the problem of climate change. It a task of politicians and responsible people in society to show that CCS is about safety and risks, not about economics, real estate and NUMBY. The public must be informed that the problem is climate change and be given both sides of the story, not only those of NGOs, and become aware of the problem and the available solutions to it. It is also a matter of public awareness of climate change and governments, society, scientists and the private sector must come into agreements on how to tackle climate change.

Lack of robust-transparent legal framework: it is a matter of political willingness and agreements to come with consistent policies on energy, climate change mitigation and possible solutions to reduce the emissions.

Renewable Energy competition: the competition with renewable energy is going to become more relevant in the long term, because the renewables will become more efficient and cheaper. It is a matter of political willingness to fund CCS demonstration in order to advance the technology and reduce the related costs.

6.5 How do different stakeholders assess the barriers and uncertainties

There were significant differences between different stakeholders on how they perceive and score the barriers for the full scale deployment of CCS. See figures 11, 12 and 13.

The most significant differences were in carbon lock-in and dependency on fossil fuel. As for the criterion carbon lock-in is concerned, for the expert of environmental group this is an important barrier since CCS is closely related to coal power plants, which relation does not lead to the real transition to renewable energy. On the contrary, for the business sector this of more a motivation and incentive for CCS, rather than a barrier. Moreover, the second most significant differences were found in the criterion of dependency on fossil fuel, which according to the academics and experts B, C from the business sector, it is a motivation and incentive for CCS instead being a barrier, for the reason why we are dependent on fossil fuel and the economic development and energy supplies rely on fossil fuels for the next decades coming, consequently CCS becomes essential. Contrary, for the expert of environmental group, the dependency on fossil fuel is part of the problem.

The most significant similarities and accordance in opinions between stakeholders were found for the criteria of the insufficient CO_2 price, the economic and financial viability, the need for stronger incentive mechanisms, the lack of robust-transparent legal framework and finally the competition with renewable energy.

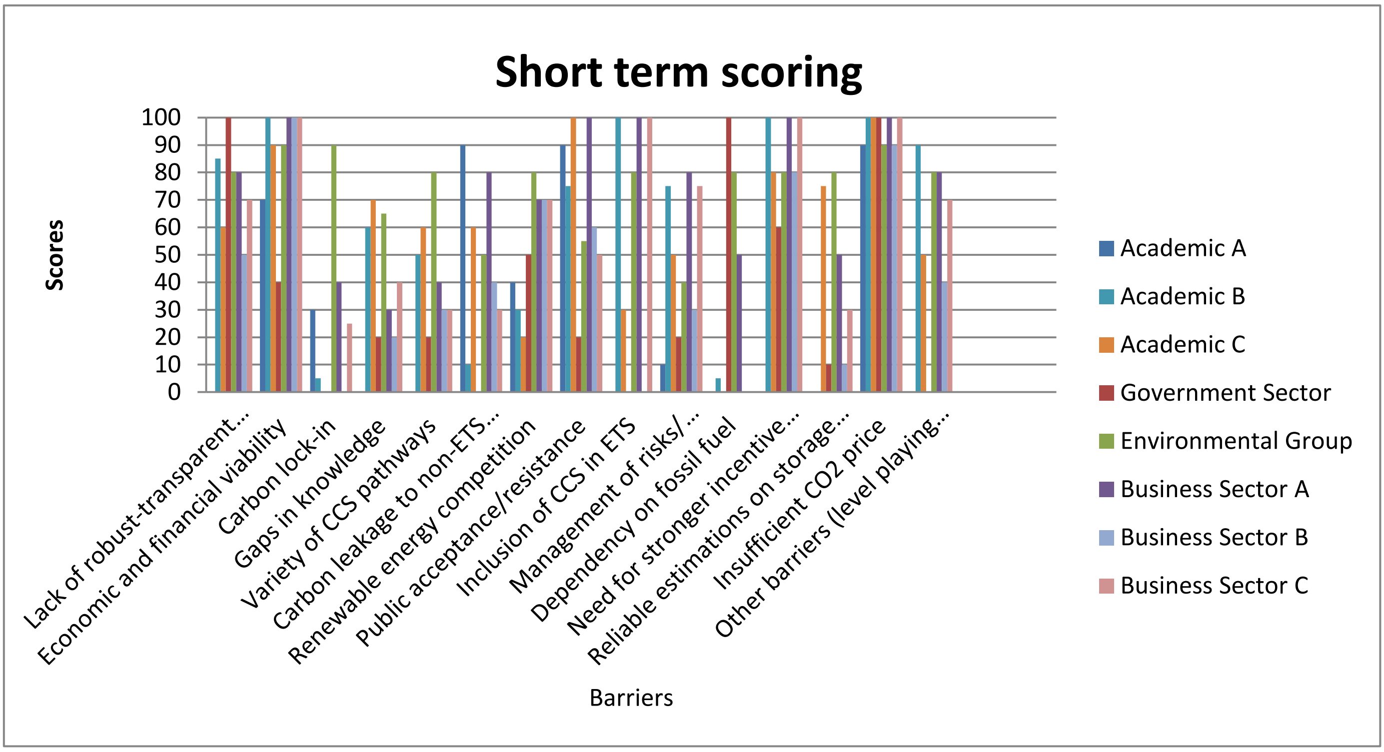

figure. 11 **Differences between experts' scores in the short term**

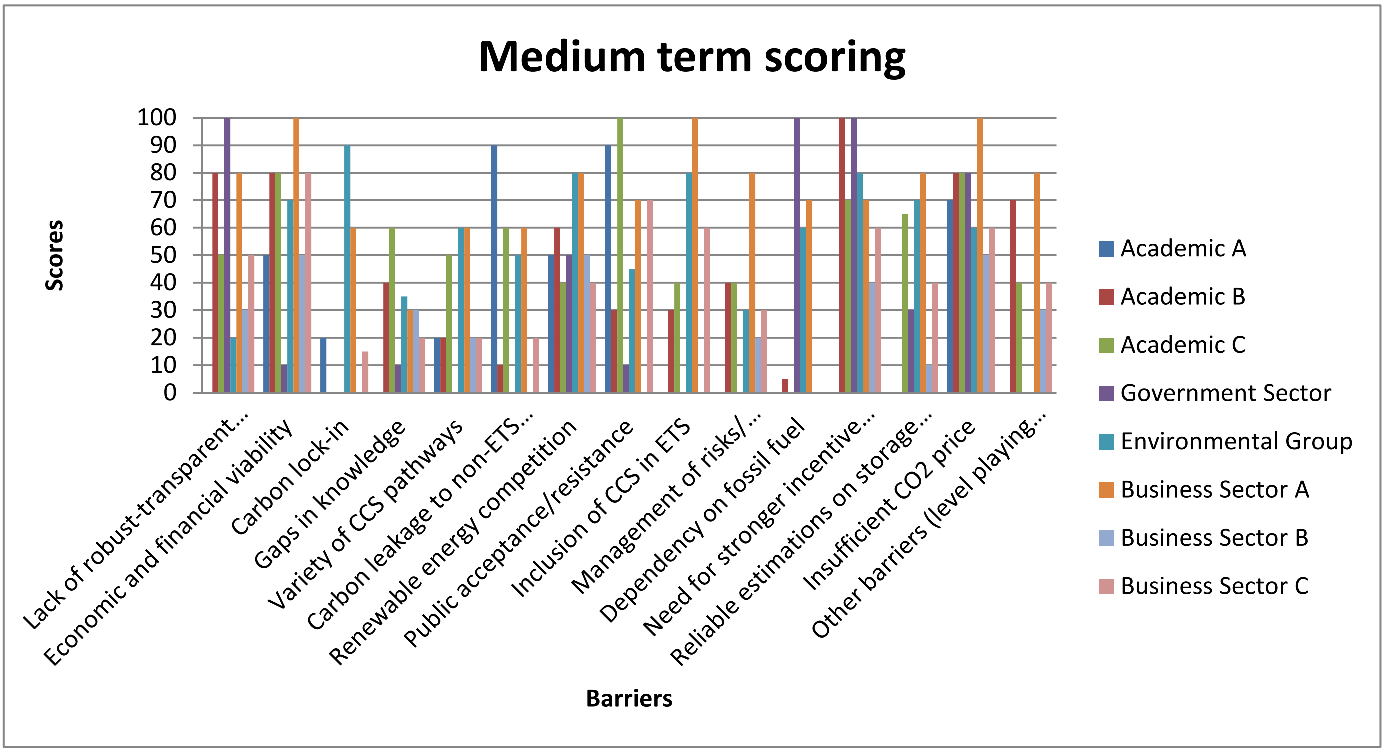

figure. 12 Differences between experts' scores in the medium term

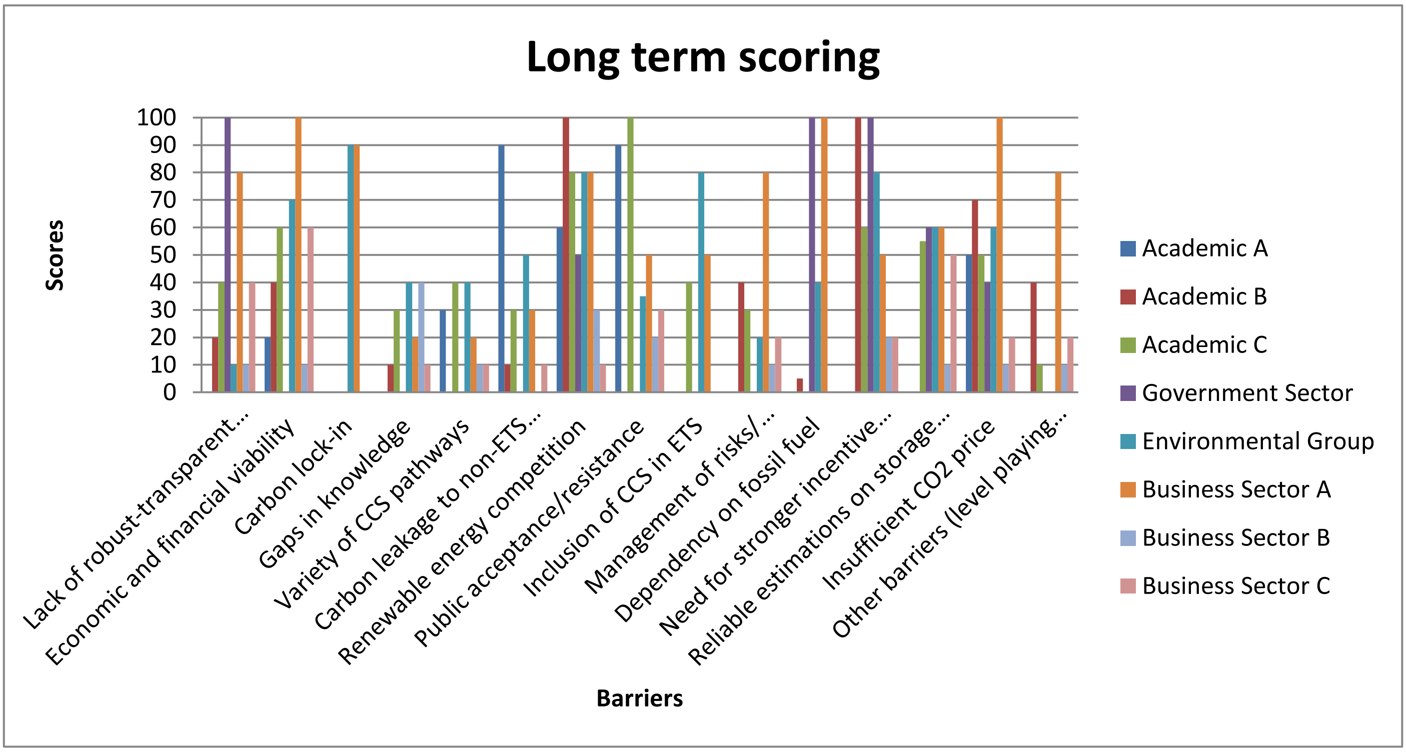

figure. 13 Differences between experts' scores in the long term

6.6 How CCS is perceived in different locations worldwide

In order to gain insights into the CCS and the barriers and uncertainties regarding the full scale deployment, the experts were asked to give an insight into how CCS is perceived in different locations worldwide, so as to tackle differences which may prove to be important for the assessment of the barriers and uncertainties. Hence, a description of how CCS is perceived in different countries follows.

In the US CCS is perceived as a business opportunity, as well as for EOR is considered. There is much less awareness of the climate change, thus it is not problem driven but technology driven. Many power plants are not built with CCS and lobbies play an important role, are very strong and frustrating all the initiatives because of the big interest in coal. Additionally there is different public opposition, mainly because of the differences in population density across the country. Finally, CCS is more financially viable.

Australia, similarly to the US, has a big interest in coal and lobby groups are powerful, playing an important role in frustrating the initiatives. Furthermore, Australia has the biggest research institute and research program in CCS worldwide.

Canada is better in combining the climate change problem solving and innovation in CCS technologies. The Canadian climate change policies are similar to those of Europe and there is a perceived need for cleaner and greener energy supplies, since the economy is dependent on coal, oil and gas exports. There is an understanding for the need for cleaner energy resources and because of this understanding and the density of population the public acceptance is larger.

In China there is much less awareness of the climate change problem and there is a very large air pollution problem. However, China sees benefits on CO_2 capturing and re-use and CCS is more business driven than climate change driven. CCS is seen as a business opportunity is terms of developing technologies, and as a competitive advantage in doing so.

Japan and South Korea, similarly to China, see CCS as an opportunity to sell innovative technology to the rest of the world and have a long tradition in CCS research. India faces a big problem with air pollution but a CO_2 market system would not work, thus has to be convinced that it is cheaper to invest in CCS, rather facing temperature increase. Finally, small things are happening in South Africa and South America. A potential big player in the future is Brazil.

In Europe there is much more awareness of the climate change problem and CCS is on a more environmental level. Europe is willing to create a market for CO_2 by pricing CO_2 and in the medium term will have a more proactive and leading role. The private sector will follow the European approach, which has appropriate intentions but is still missing the appropriate outcome because of the different national policies on climate change and the energy problem. Eastern Europe is not yet convinced for the need of CCS, contrary to the Western Europe. Even though EU does not support financially anymore pilot projects, CCS fits in the emission reduction strategy for climate change.

Summary

In this chapter there was a description of how the barriers and uncertainties identified by the author were perceived by the experts interviewed. The assessment of the barriers for the full scale deployment of CCS for the short term, medium term and long term resulted in that the most important ones are the economic and financial viability, the insufficient CO_2 price, the need for stronger incentive mechanisms, the public acceptance, the lack of a robust-transparent legal framework and the renewable energy competition.

The barrier of economic and financial viability can be overcome by the proper use of ETS, the reduction in emission caps and the research on other possibilities of CO_2 usage. The insufficient CO_2 price is related to ETS and its proper function, which is a matter of political willingness and agreements between key players to come with consistent energy policies. It is also again a matter of political willingness to come with stronger incentive mechanisms, agreements and convince the society that there is a need for more consistent and tough energy policies. In order to overcome the barrier of public acceptance and resistance the politicians have to involve the public into the discussion, inform the public on climate change and show the interdependency between CO_2 and climate change and the options available to address the problem of climate change. Governments, society, scientists and the private sector must come into agreements on how to tackle climate change. Political willingness and agreements to come with consistent policies on energy, climate change mitigation and possible solutions to reduce the emissions is also necessary to come with robust and transparent legal framework. Finally, it is a matter of political willingness to fund CCS demonstration in order to advance the technology and reduce the associated costs.

During the interviews the experts stated that there are also additional barriers for the full scale deployment of CCS, such as the political urgency of climate change, the willingness to pay more for our energy supplies, the lack of infrastructure, the efficiency of CO_2 capturing process, the unawareness of the climate change by the public, the lack of global framework and the differences in views between different stakeholders.

The most significant differences between stakeholders' perceptions on the barriers and uncertainties were found in carbon lock-in and dependency on fossil fuel, which apart from the expert of the environmental group who sees these two criteria as barriers, the rest of the participants find them instead as a motivation and incentive for CCS. The most significant similarities and accordance in opinions between stakeholders were found for the criteria of the insufficient CO_2 price, the economic and financial viability, the need for stronger incentive mechanisms, the lack of robust-transparent legal framework and finally the competition with renewable energy.

Amongst the experts interviewed, five believe that in the short term the full scale deployment of CCS is minimum feasible while the rest three believe that it is less feasible. For the medium term scenario, four experts believe that it is less feasible, for one is neutral and for the rest three is more feasible. As for the long term scenario is concerned, two experts find the full scale deployment less feasible, one finds it neutral, three considered it more feasible and the rest two as maximum feasible.

Concluding, in Europe there is much more awareness of the climate change problem and CCS is on a more environmental level. Even though EU does not support financially anymore pilot projects, CCS fits in the emission reduction strategy for climate change. The Canadian climate change policies are similar to those of Europe and there is a perceived need for cleaner and greener energy supplies and a good combination of the climate change problem solving and innovation in CCS technologies. For the US, Australia and China CCS is more business driven than climate change driven.

CHAPTER 7

DISCUSSION

Carbon Capture and Storage (CCS) is nowadays often considered to be a crucial technology in the long term carbon abatement strategies of many countries and international organizations (Markusson, Kern, & Watson, 2010). If effective, such CO_2 capture and storage technologies (CCS) would allow the continued use of fossil fuels with reduced concerns about climate destabilization (Sathre, Chester, Cain, Masanet, 2012). However, despite its potential, the technology has yet to be proven as an integrated system at a full-scale so as to be an effective way of climate change mitigation, taking into consideration the viability, maturity and impacts. While CCS is seen as vital by some actors, others claim it is not an attractive option and may not be a necessary part of the transition towards a low carbon economy (Meadowcroft, Langhelle, 2009).

While CCS is now entering a phase of demonstration of full scale integrated systems in various locations around the world (de Coninck et al., 2009), there are still significant technical, economic, political and financial uncertainties about CCS (Markusson, Kern, Watson, 2010). As a result, the relevant uncertainties create challenges for the stakeholders who want to see CCS technology at a full scale deployment and as a tool for global climate change mitigation strategies. A great challenge for the stakeholders is that the number of barriers and uncertainties for the full scale deployment of CCS is too high. The aim of this thesis consequently, was to identify the barriers and uncertainties related to the full scale deployment of CCS and make an assessment of them. It was also part of the research questions how do different stakeholders assess the barriers and how the barriers and uncertainties identified can be overcome.

In order to identify the barriers and uncertainties for the full scale deployment of CCS, a literature review from existing social science literature was conducted. Afterwards, the Multi-Criteria Analysis (MCA) was chosen as the proper methodology in assessing these barriers. There were created three scenarios, a short term (2013-2020), a medium term (2020-2030) and a long term (2030-beyond) so as to assess the barriers and uncertainties against these three scenarios. The initial planning was to conduct a qualitative internet survey, by the use of questionnaires, sent to stakeholders on CCS worldwide, also in order to give insights into the research question on how the barriers are assessed by stakeholders in different locations globally. Unfortunately, there was only one response; therefore this research question was not possible to be answered.

Alternatively, the research was carried on with interviews with experts in the Netherlands, three academics, three from the business sector, one from the government sector and one from an environmental group. The purpose was to cover the whole range of stakeholders (governmental, business, scientific, and societal) so as to gain useful insights and provide with answer the research question on how different stakeholders assess the barriers. Based on the ex-ante expectation of the writer that the expertise of the experts interviewed was similar, there was no weight application on the barriers during the scoring process. A more robust approach would be to engage a wider range of experts across the assessment and to interview more specific experts in each sector. The study revealed the following key points regarding the full scale deployment of CCS:

Barriers and uncertainties for the full scale deployment of CO_2 Capture and Storage (CCS)

The first research question that this thesis aimed at answering was to identify the barriers and uncertainties for the full scale deployment of CCS. The barriers identified by the literature review from existing social science literature were the lack of robust-transparent legal framework, the economic and financial viability, the carbon lock-in, the gaps in knowledge, the variety of CCS pathways, the carbon leakage to non-ETS countries, the renewable energy competition, the public acceptance-resistance, the inclusion of CCS in ETS, the management of risks and externalities, the dependency on fossil fuel, the need for stronger incentive mechanisms, the reliable estimations on storage capacity, the insufficient CO_2 price and other barriers (level playing field/coal tax).

The process of interviewing experts from the governmental, business, academic and environmental sector and their assessment of those barriers revealed that the most important barriers for the full scale deployment of CCS are the economic and financial viability, the insufficient CO_2 price, the need for stronger incentive mechanisms, the public acceptance, the lack of robust-transparent legal framework and the renewable energy competition.

Of moderate importance were ranked the barriers and uncertainties of the variety of CCS pathways, the gaps in knowledge, the inclusion of CCS in ETS, the management of risks and externalities, the reliable estimations on storage capacity and other barriers (level playing field/coal tax).

The carbon leakage to non-ETS countries was mostly perceived as an associated risk and not as a barrier for the full scale deployment of CCS. Furthermore, the carbon lock-in and dependency on fossil fuel were proved to be an incentive and motivation for the deployment of CCS, rather than a barrier. It was only the expert form the environmental group the perceived these two criteria as barriers.

The process of interviewing experts also interestingly revealed that apart from the barriers identified by the writer, there are additional barriers to consider and assess for the deployment of CCS. The additional barriers are the political urgency of climate change, the willingness to pay more for our energy supplies, the lack of infrastructure, the efficiency of CO_2 capturing process, the unawareness of the climate change by the public, the lack of global framework and the differences in views between different stakeholders.

Full scale deployment of CCS in the short term (2013-2020)

This research resulted in that in the short term scenario the most important barriers to overcome for the full scale deployment of CCS are by descending order the insufficient CO_2 price, the economic and financial viability, the need for stronger incentive mechanisms, the lack of robust and transparent legal framework and the public acceptance/resistance. Of moderate importance are the inclusion of CCS in ETS, the other barriers (level playing field/coal tax), the renewable energy competition, the management of risks and externalities. The least important are the risk of carbon leakage to non-ETS countries the variety of CCS pathways, the gaps in knowledge, the reliable estimations on storage capacity and dependency on fossil fuel and carbon lock-in.

As for the feasibility of full scale deployment of CCS in the short term scenario, five of the experts interviewed, business sector A, B, C, governmental sector and academic C found that the full scale deployment of CCS by 2020 is minimum feasible, while academics A, B and the expert of the environmental group found it less feasible.

Full scale deployment of CCS in the medium term (2020-2030)

Taking into consideration the full scale deployment of CCS in the medium term, the findings of this thesis are that the most important barriers and uncertainties by descending order are: the need for stronger incentive mechanisms, the insufficient CO_2 price, the economic and financial viability, the public acceptance/resistance and the lack of robust-transparent legal framework and renewable energy competition. Compared to the short term, the need for stronger incentive mechanisms becomes the most important factor. Of moderate importance are the inclusion of CCS in ETS, the other barriers, the reliable estimations on storage capacity and the risk of carbon leakage to non-ETS countries. The least important are the variety of CCS pathways, the management of risks and externalities, the dependency on fossil fuel, the gaps in knowledge and the carbon lock-in.

As for the feasibility of full scale deployment in the medium term, it is considered as less feasible by academics A, C and experts B, C from business sector. For academic B is neutral, while for experts A from business sector, governmental sector and environmental sector is more feasible.

Full scale deployment of CCS in the long term (2030-beyond)

In the long term scenario, the need for stronger incentive mechanisms remains the most important barrier to overcome for the full scale deployment of CCS, same as in the medium term scenario. The second most important becomes the renewable energy competition since by that time the renewables will have became better and cheaper. The third most important barrier is the insufficient CO_2 price and fourth follows the economic and financial viability. The public resistance becomes less important compared to the short and medium term, the same as the inclusion of CCS in ETS. However in the long term the carbon lock in and the dependency on fossil fuel will become more relevant while the variety of CCS pathways and the gaps in knowledge will be the less important.

In the long term scenario, the feasibility for full scale deployment of CCS is less for academics A, C, neutral for business sector C, more for academic B, environmental group and business sector B. finally it is considered maximum feasible for experts A from business sector and expert from governmental sector. The full scale deployment becomes more feasible in the long term when compared to the short term.

Inter-linkages between barriers

The assessment of the barriers and uncertainties during the interview process with the experts revealed that there are significant inter-linkages and dependency between the barriers and uncertainties. The economic and financial viability is dependent on the CO_2 price, which affects the renewable energy competition. The carbon lock-in is linked to the dependency on fossil fuel which also reflects the renewable energy competition. The gaps in knowledge are also related to the variety of CCS pathways and the economic and financial viability reflects the lack of robust and transparent legal framework. The inter-linkages found mean that different barriers can be interpreted and scored differently by different stakeholders thus influencing the assessment and making hard to come to strong conclusions.

Differences between stakeholders

An objective of this thesis was also to answer to the research question on how do different stakeholders assess the barriers. The assessment process by the experts interviewed revealed that there were significant differences between different stakeholders on how they perceive and score the barriers for the full scale deployment of CCS. The most significant differences were found in carbon lock-in and dependency on fossil fuel. As for the criterion carbon lock-in is concerned, for the expert of environmental group this is an important barrier since CCS is closely related to coal power plants, which relation does not lead to the real transition to renewable energy. On the contrary, for the business sector this more of a motivation and incentive for CCS, rather than of a barrier. Moreover, the second most significant difference were found in the criterion of dependency on fossil fuel, which according to the academics and experts B, C from the business sector, it is a motivation and incentive for CCS instead being a barrier, for the reason why we are dependent on fossil fuel and the economic development and energy supplies rely on fossil fuels for the next decades coming, consequently CCS becomes essential. Contrary, for the expert of environmental group, the dependency on fossil fuel is part of the problem. The differences in opinions between a small sample of different stakeholders indicate that investments on CCS is a very complicated issue and these differences make it even more difficult when a large number of different stakeholders has to come into table and make decisions.

CCS in Rotterdam, the Netherlands

In the case of Port of Rotterdam and the City of Rotterdam, economic development depends to a large degree on energy and emission intensive industries and the power sector. The Port of Rotterdam is one of the largest industrial and petrochemical clusters in Europe and includes five refineries, two coal-fired power plants, two gas-fired power plants and some twenty chemical plants. Taking into consideration that the CO_2 emissions are expected to increase in the upcoming years, the Port of Rotterdam, the City of Rotterdam, port and industries' association Deltalinqs, and the DCMR Environmental Protection Agency committed themselves to Rotterdam Climate Initiative (RCI), which is aims to achieve a fifty percent reduction of CO_2 emissions in the Rotterdam region by 2025, as compared to 1990, to climate-proof and adapt the city to the consequences of climate change and to strengthen the Rotterdam economy(RCI, 2011).

For some of the experts interviewed the targets of RCI are considered to be very ambitious and not at all realistic and in order to reach them there has to be full scale deployment of CCS in power plants, refineries and petrochemical plants. While for others, the goals aforementioned, even though the signals within the last two years are not the rights ones, they are a good incentive, a good step forward and not impossible. In any case though, even if RCI goals are difficult to be reached, the need for CCS in Port of Rotterdam and the metropolitan region is perceived as urgent, because there are no other real alternatives than capturing CO_2 and CCS is the only solution in doing so, and also towards the transition to sustainability.

CCS in Port of Rotterdam is seen by the experts only as a part of mitigation mix strategy in order to ensure growth, economic development and transition to sustainability. It is very important for the Port of Rotterdam to remain an energy port and given the fact that there is so much energy production in the area, CCS is the only effective technology in doing so. However, apart from CCS, the mitigation mix strategy includes energy efficiency, for instance waste heat and steam, a source oriented approach, as much re-use of CO_2 as possible, biomass, renewable energy and innovation in production processes.

CCS, apart from playing a crucial role in achieving the objectives of the Rotterdam Climate Initiative regarding the emissions reduction, plays also a crucial role in whether Port of Rotterdam will become a CO_2 hub of Northwest Europe by 2050 or not. The location of the port and the existing port infrastructure make it possible to happen, there is the opportunity of using Germany's captured CO_2 and it is considered also economically viable. It depends though on whether the ETS will work properly, the price of CO_2, the strong support from the government and cooperation between actors. It is also a technology challenge, regarding the capturing process which is very energy intensive, and CCS will have to be a proven technology. Without CCS full scale deployment this is unlikely to happen. If CCS will be deployed in Europe, then Port of Rotterdam is the only potential CO_2 hub in Europe because of its strategic location, its access to deep sea water and rivers, the logistics activities and the presence of one of the world's main industrial cluster and economies of scales. The UK and Norway was also considered to be potential CO_2 hubs in Europe by expert B from business sector. According to academic C and expert form the environmental group, Port of Rotterdam will not become a CO_2 hub for the reason why by 2050 the greener economy will already be a reality in which a CO_2 hub will not fit in and CCS should not be part of port's development.

Policy recommendations

It is a matter of political willingness to convince and inform the public about climate change, its impacts on the environment and show the interdependency between CO_2 and climate change and the options available to address the problem. Political willingness is crucial to come with consistent policies on energy, climate change mitigation and possible solutions to reduce the emissions. It is not only urgent to convince the society about the climate change, but also to involve the public into the discussion and come to agreements with the society, the scientists and the private sector on how to tackle climate change. It depends on political willingness to come with stronger incentive mechanisms, robust and transparent legal framework, global framework, ensure that ETS is working properly and fund CCS demonstration projects so as to advance the technology and reduce the associated costs. The differences in views between different stakeholders make it even harder to come into agreements on how to tackle climate change, which is also the case for CCS. The discussions on CCS are hard to be objective between NGOs, the business sector, the scientists, the governments and the public, this is why the urgency of climate change is crucial. The governments are responsible for regulating, setting the targets, forming the public opinion and giving proper incentives to the private sector to do the technology change, act and operate. There is an urgent need for cooperation and collaboration on scaling up CCS deployment on a global level, since climate change is a global and not a national or regional problem. Concluding, the year 2013 is a crucial year for the first phase of development of CCS not only in Rotterdam, the Netherlands, but also in Europe, since ROAD project is taking its final investment decision, which will have a domino effect in other projects related to infrastructure.

Limitations

The aim of this thesis was to assess the barriers and uncertainties related to the full scale deployment of CCS and how these barriers are perceived by different stakeholders. For this purpose, the methodology of Multi Criteria Assessment was chosen as the most appropriate. The interviews with experts included a small sample of eight different experts covering the whole stakeholders range: governmental, scientific, business and environmental, which can only be indicative. Furthermore, there was no weight application on the barriers during the scoring process, based on the ex-ante expectation of the writer that the expertise of the experts interviewed was similar, which if was not taken into account may would have led to different results. During the interviews there proved to be dependency on the barriers and uncertainties and the scoring was based on the personal interpretation of the experts. Finally, during the interviewing process there proved to be additional barriers and uncertainties for the full scale deployment of CCS which were not included in the assessment.

Further research

This paper can be a motivation for further research on assessing not only the barriers and uncertainties identified by the writer, but also the additional barriers and uncertainties identified during the interview process, taking into account that the level of expertise of the experts is not similar, thus applying weighting on the scores for each criterion, and assess the criteria with respect to how dependency is treated. A larger number of experts from the governmental, scientific, business and environmental and societal sectors will lead to more robust results.

CHAPTER 8

CONCLUSIONS

Carbon Capture and Storage (CCS) is nowadays considered to be a crucial technology regarding the carbon abatement strategies in order to tackle irreversible climate change. If effective, such CO_2 capture and storage technologies would allow the continued use of fossil fuels with reduced concerns about climate destabilization (Sathre, Chester, Cain, Masanet, 2012). However, despite its potential, the technology has yet to be proven as an integrated system at a full-scale so as to be an effective way of climate change mitigation, taking into consideration the viability, maturity and impacts. While CCS is seen as vital by some actors, others claim it is not an attractive option and may not be a necessary part of the transition towards a low carbon economy (Meadowcroft, Langhelle, 2009).

Although demonstration of full scale integrated CCS systems in various locations globally is already taking place, there are still significant technical, economic, political and financial barriers and uncertainties about. As a result, the relevant uncertainties create challenges for the stakeholders who want to see CCS technology at a full scale deployment and as a tool for global climate change mitigation strategies. A great challenge for the stakeholders is that the number of barriers and uncertainties for the full scale deployment of CCS is too high. The aim of this thesis therefore, was to identify the barriers and uncertainties related to the full scale deployment of CCS and make an assessment of them. It was also part of the research questions how do different stakeholders assess the barriers and how the barriers and uncertainties identified can be overcome. The methodology chosen was the Multi-Criteria Assessment (MCA) in which three scenarios were created, short, medium and long term against which the barriers and uncertainties were assessed. Eight experts from the governmental, scientific, business and environmental sector were interviewed. The main findings of the research follow.

In the short term (2013-2020), the most important barriers to overcome for the full scale deployment of CCS are by descending order the insufficient CO_2 price, the economic and financial viability, the need for stronger incentive mechanisms, the lack of a robust and transparent legal framework and the public acceptance/resistance.

In the medium term (2020-2030), the most important barriers and uncertainties by descending order are: the need for stronger incentive mechanisms, the insufficient CO_2 price, the economic and financial viability, the public acceptance/resistance, the lack of a robust-transparent legal framework and renewable energy competition.

Compared to the short term, the need for stronger incentive mechanisms becomes the most important factor.

In the long term (2030-beyond), the need for stronger incentive mechanisms remains the most important barrier to overcome for the full scale deployment of CCS, same as in the medium term scenario. The second most important barrier becomes the renewable energy competition and the third most important barrier is the insufficient CO_2 price. Fourth follows the economic and financial viability. The public resistance becomes less important compared to the short and medium term, the same as the inclusion of CCS in ETS.

The process of interviewing experts also interestingly revealed that apart from the barriers identified by the writer, there are additional barriers to consider and assess for the deployment of CCS. The additional barriers are the political urgency of climate change, the willingness to pay more for our energy supplies, the lack of infrastructure, the efficiency in CO_2 capturing process, the unawareness of the climate change by the public, the lack of a global framework and the differences in views between different stakeholders.

The assessment process by the experts interviewed revealed that there were significant differences between different stakeholders on how they perceive and score the barriers for the full scale deployment of CCS. The most significant differences were found in carbon lock-in and dependency on fossil fuel, which are perceived as a motivation and incentive for the deployment of CCS for all of the experts interviewed, apart from the expert of the environmental group, who finds that CCS is closely related to coal power plants, which close relation does not lead to the real transition to renewable energy.

The barrier of economic and financial viability can be overcome by the proper function of ETS, the reduction in emission caps and the research on other possibilities of CO_2 usage. The insufficient CO_2 price is related to ETS and its proper function, which is a matter of political willingness and agreements between key players to come with consistent energy policies. It is also again a matter of political willingness to come with stronger incentive mechanisms, agreements and convince society that there is need for more consistent and tough energy policies. In order to overcome the barrier of public acceptance and resistance, politicians have to involve the public into the discussion, inform the public on climate change and show the interdependency between CO_2 and climate change and the options available to address the problem of climate change. Governments, society, scientists and the private sector must come into agreements on how to tackle climate change. Political willingness and agreements to come with consistent policies on energy, climate change mitigation and possible solutions to reduce the emissions is also necessary to come with robust and transparent legal framework. Finally, it is a matter of political willingness to fund CCS demonstration in order to advance the technology and reduce the associated costs. The governments are responsible for regulating, setting the targets, forming the public opinion and giving proper incentives to the private sector to realize the technology change, act and operate. There is an urgent need for cooperation and collaboration on scaling up CCS deployment on a global level, since climate change is a global and not a national or regional problem.

Bibliography

ACCSEPT. (2007). Stakeholder Perceptions of CO2 Capture and Storage in Europe: Results from the EU-funded ACCSEPT Survey. *Shackley S., Waterman H., Godfroij P., Reiner D., Anderson J., Draxlbauer K., de Conich H., Groenenberg H., Flach T., Sigurthorsson G.*

Arthur, W., & Brian. (1989). Competing technologies and lock-in by historical small events. *Economic Journal , 99*, pp. 116-131.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, H., et al. (2007). CO2 storage capacity estimation: methodology and gaps. *Int. J. Greenhouse Gas Control , 1*, pp. 430-443.

Bolland, O. (2009). Course EP8113: Thermal power cycles and cogeneration, Norwegian University of Science and Technology.

Boots, M. (2003). Green certificates and carbon trading in the Netherlands. *Energy Policy , 31* (Issue 1), pp. 43–50.

Coates, J. F. (2001). A 21st century agenda for technology assessment. *Forecast. Soc. Change*, *67* (2-3), pp. 303-308.

Coates, J. F. (1976). The role of formal models in technology assessment. *Technol. Forecast. Soc. Change , 9* (1-2), pp. 139–190.

Curran, M. (1996). Environmental Life-Cycle Assessment. *McGraw- Hill, London, New York* .

Daskalakis, G., Psychoyios, D., & Markellos, R. N. (2009). Modeling CO2 emission allowance prices and derivatives: Evidence from the European trading scheme. *Journal of Banking & Finance , 33* (7), pp. 1230–1241.

David, P. A. (1985). Clio and the economics of QWERTY. *American Economic Review , 75* (2).

Dberr. (2008). Towards Carbon Capture and Storage. A Consultation Document . *DBERR* .

de Coninck, H., Flach, T., Curnow, P., Richardson, P., Anderson, J., Shackley, S., et al. (2009). The acceptability of CO2 capture and storage (CCS) in Europe: An assessment of the key determining factors Part 1. Scientific, technical and economic dimensions. *International Journal of Greenhouse Gas Control , 3*, pp. 333-343.

Desbarats, J., & et, a. (2010). Review of the public participation for CCS and non-CCS projects in Europe. *Institute for European Environmental Policy* .

Dodgson, J., Spackman, M., Pearman, A., & Phillips, L. (2001). Multi-Criteria Analysis: A Manual.

DTI. (2003). *Department of Trade and Industry*. Retrieved from www.dti.gov.uk.

ECN. (2008). Retrieved from www.ecn.nl/docs/library/report/2007.

EPRI. (2011). *Electric Power Research Institute*. Retrieved from www.epri.com.

European Commission. (2007a). Sustainable Power Generation from Fossil Fuels: Aiming for Near-Zero Emissions from Coal after 2020. *COM(2006)843 Final. [SEC(2006)1722, SEC(2006)1723, SEC(2007)12]*. European Commission, Brussels.

European Commission. (2008a). Proposal for a Directive of the European Parliament and of the Council on the Geological Storage of Carbon Dioxide and Amending Council Directives 85/337/EEC, 96/61/EC, *Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No 1013/2006. COM(2008)18 Final. [COM(2008)30 Final, SEC(2008)54, SEC(2008)55]*. European Commission, Brussels

European Commission. (2008b). Impact Assessment, Commission Staff Working Document. Accompanying Document to the Proposal for a Directive of the European Parliament and of the Council on the Geological Storage of Carbon Dioxide. *COM(2008) x Final. [SEC(2008) x, SEC(2008)x]*. European Commission, Brussels.

European Commission, 2008c. Communication of the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Supporting Early Demonstration of Sustainable Power Generation from Fossil Fuels. COM(2008)13 Final. [COM(2008)30 Final, SEC(2008)47, SEC(2008)48]. European Commission, Brussels.

Genus, A. (2006). Rethinking constructive technology assessment as democratic, reflective, discourse. *Technological Forecasting & Social Change , 73*, pp. 13–26.

Gibbins, J., Liang, X., Reiner, D., & Li, J. (n.d.). Financing Capture Ready: Issuing Tradable Capture Option. *University of Cambridge ,Imperial College London* .

Gough, C., & Shackley, S. (2005). Towards a multi-criteria methodology for assessment of geological carbon storage options. *Tyndall Centre for Climate Change Research, University of Manchester*.

Greenpeace. (2008). The Case Against Coal-Fired Power Generation.

Guston, D. H., & Sarewitz, D. (2001). Real-time technology assessment. *Technology in Society*, *24* (1), pp. 93-109.

Haugen, H. A., Aagaard, P., Thyberg, B., Kjärstad, J., Langlet, D., Melaaen, M. C., et al. (2011). CCS in the Skagerrak/Kattegat area. *Energy Procedia , 4*, pp. 2324–2331.

Huang, Y., Rezvani, S., McIlveen-Wright, D., Minchener, A., & Hewitt, N. (2008). "Techno-economic study of CO2 Capture and Storage in coal fired oxygen fed entrained flow IGCC power plants". *Fuel Processing Technology , 89*, pp. 916-925.

Huijts, N., Midden, C., & Meijnders, A. (2007). Social acceptance of carbon dioxide storage. *Energy Policy , 35* (5), pp. 2780-2789.

Huizeling, E., Rosa, M., Schoenmakers, H., Irons, R., & Boon, G. (2011). CCS project development in Rotterdam. *Energy Procedia , 4*, pp. 5661–5668.

IEA. (2008b). Energy Technology Perspectives, OECD/ IEA, Paris.

IEA. (2006). *International Environmental Agency*. Retrieved from www.iea.org.

IEA. (2009). Technology roadmap: carbon capture and storage.

IEA. (2007). World Energy Outlook. International Energy Agency, Paris.

Intergovernmental Panel on Climate Change, The Physical Science Basis. (2011). From www.ipcc.ch.

International Energy Agency. (2011). From www.iea.org.

IPCC. (2005). Special report on carbon dioxide capture and storage. In: Metz, B., Davidson, O., de Coninck, H., Loos, M., Meyer, L, Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

IPCC. (2007). Climate Change Mitigation. In: Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L., Working Group III's contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Janssen, R. (2001). On the Use of Multi-Criteria Analysis in Environmental Impact Assesment. *Journal Of Multi-Criteria Desicion Analysis , 10*, pp. 101–109.

Jordal, K., Anheden, M., Yan, J., & Stromberg, L. (2004). Oxyfuel combustion for coal-fired power generation with CO2 capture- opportunities and challenges. *7th International Conference on Greenhouse Gas Technologies, Vancouver, Canada* .

Kasemir, B., Jager, J., Jaeger, C., & Gardner, M. (2003). Public Participation in Sustainability Science, A Handbook. *Cambridge University Press* .

Keeney, R., & Raiffa, H. (1993). Decisions with Multiple Objectives: Preferences and Value Trade-offs. *Cambridge University Press* .

Koo, J., Han, K., & Yoon, E. S. (2011). Integration of CCS, emissions trading and volatilities of fuel prices into sustainable energy planning, and its robust optimization. *Renewable and Sustainable Energy Reviews , 15*, pp. 665–672.

Lockwood, M. (2008). After the Coal Rush: Assesing Policy Options for Coal-Fired Electricity Generation. *Institute for Public Policy Research* .

Markusson, N., & Haszeldine, S. (2008). How ready is 'capture ready'? *Scottish Centre for Carbon Storage, Uiversity of Edinburgh* .

Markusson, N., Kern, F., & Watson, J. (2010). Assessing CCS viability - A socio-technical framework. *Energy Procedia* .

Meadowcroft, J., & Langhelle, O. (2009). The politics and policy of CCS: the uncertain road ahead, in Caching the Carbon. The Politics and Policy of Carbon Capture ans Storage. pp. 267-296.

Mikundaa, T., van Deurzen, J., Sebregts, A., Kerssemakers, K., Tetteroo, M., & Buit, L. (2010). Towards a CO2 infrastructure in North-Western Europe: Legalities, costs and organizational aspects. *Energy Procedia* .

MIT. (2007). The future of Coal: Options for a Carbon-Constrained World. Massachusetts Institute of Technology, Cambridge MA, USA.

Mizrach, B. (2012). Integration of the global carbon markets. *Energy Economics , 34*, pp. 335-349.

Morris, P., & Therrivel, R. (2001). Methods of Environmental Impact Assessment. *Spon Press*.

Neele, F., Wu, H., Hendriks, C., & Brandsma, R. (2004). Planning of CCS development in the Netherlands offshore. *Energy Procedia , 4*, pp. 2756-2763.

Pearce, D., & Turner, K. (1989). Economics of Natural Resources and the Environment. *Prentice Hall* .

Renn, O., Webler, T., & Wiedemann, P. (1995). Fairness and Competence in Citizen Participation– Evaluating Models for Environmental Discourse. *Kluwer Academic Publishers* .

Rodemeyer, M., Sarewitz, D., & Wilsdon, J. (2005). The Future of Technology Assessment. *Woodrow Wilson International Center for Scholars* .

Rotterdam, Climate, & Initiative. (2011, May). CO2 capture and storage in Rotterdam. *updated edition*.

Rubin, E., et. al., (2004). Learning curves for environmental technology and their importance for climate policy analysis. *Energy , 29* (9-10), pp. 1551-1559.

Sathre, R., Chester, M., Cain, J., & Masanet, E. (2012). A framework for environmental assessment of CO2 capture and storage systems. *Energy , 37*, pp. 540-548.

Schokkenbroek, H., Slagter, M., Wellenstein, E., Hendriks, C., & Koornneefb, J. (2011). Elements for aNational Master Plan for CCS — Lessons learnt. *Energy Procedia* , pp. Pages 5810–5813.

Schot, J., & Rip, A. (1996). The Past and Future of Constructive Technology Assessment. *Technological Forecasting and Social Change , 54*, pp. 251-268.

Schreuder, Y. (2011 30June-2July). Unintended Consequences: Climate Change Policy in a Globalizing World. *Nature Inc. Conference.* The Hague, The Netherlands.

Scrase, J. I., & Watson, J. (2009). Strategies for the deployment of CCS technologies in the UK: a critical review. *Energy Procedia , 1*, pp. Pages 4535–4542.

Sevenster, M. (2007). New electricical power plants in the Netherlands; the forgotten costs in the picture. *Centrum voor Energiebesparing Delft* .

Shackley, S., & et, a. (2009). The acceptability of CO2 capture and storage (CCS) in Europe: An assessment of the key determining factors Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation. *International Journal of Greenhouse Gas Control , 3* (3), pp. 344-356.

Stirling, A., & Mayer, S. (1999). Confronting Risk: A pilot Multi-Criteria Mapping of a GM Crop in Agricultural Systems in the UK. *Final Report prepared for the UK Roundtable on Genetic Modification* .

Teir, S., Tsupari, E., Arasto, A., Koljonen, T., Karki, J., Lehtila, A., et al. (2011). Prospects for application of CCS in Finland. *Energy Procedia , 4*, pp. 6174-6181.

Tran, T. A., & Daim, T. (2008). A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting & Social Change , 75*, pp. 1396–1405.

USDOE. (2007). *U.S Department of Energy*. Retrieved from energy.gov.

van Alphen, K., & al., e. (2009). The performance of the Norwegian carbon dioxide, capture and storage innivation system. *Energy Policy , 37* (1), pp. 43-55.

van Alphen, K., Hekkert, M., & Turkenburg, W. (2010). Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system. *International Journal of Greenhouse Gas Control , 4* (2), pp. 396-409.

van Alphen, K., van Voorst, Q., Hekkert, M. P., & Smits, R. E. (2007, August). Societal acceptance of carbon capture and storage technologies. *Energy Policy , 35* (8), pp. Pages 4368–4380.

Vergragt, P. J. (2009). CCS: the next technological lock-in? *Paper for GIN Conference "Joint Action on Climate Change", Aalborg* .

Viebahn, P., Nitsch, J., Fischedick, M., Esken, A., Schuwer, D., Supersberger, N., et al. (2007). Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic and ecological aspects in Germany. *International Journal of Greenhouse Gas Control* (I), pp. 12 1 – 133.

Wynne, B. (1975). The rhetoric of consensus politics: a critical review of technology assessment. *Research Policy , 4* (2), pp. 108-158.

Zakkour, P., Dixon, T., & Cook, G. (2011). Financing early opportunity CCS projects in emerging economies through the carbon market: mitigation potential and costs. *Energy Procedia , 4*, pp. 5692–5699.

Zapp, P., Schreiber, A., & Kuckshinrichs, w. (2009). Environmental Assessment of German electricity production from coal-fired power plants with amine-based carbon capture. *International Journal of Life Cycle Assessment , 14*, pp. 547-559.

ZEP. (2012). *Zero Emissions Platform*. Retrieved from www.zeroemissionsplatform.eu.

APPENDIX INTERVIEWS

This appendix shows which people were interviewed, their professional role and the questions asked during the interviews.

Experts:

Prof. dr. Harry Geerlings,

Professor in Governance of Sustainable Mobility at Erasmus University Rotterdam

Mr. R. Melieste,

Director Energy and Industry at Port of Rotterdam

Mr. S. Verburg,

Consultant Underground Infrastructure at Port of Rotterdam

Mr. B. van Engelenburg,

Senior Expert Energy at DCMR Milieudienst Rijnmond, Senior Policy Advisor at Rotterdam Climate Initiative

Mr. R. Moene,

Teamlead CO_2 *Capture R&D at Shell Global Solutions*

Mr. T. Bertels,

Manager CCS Portfolio, Shell International E&P

Prof. dr. Ir. J. Rotmans,

Professor in Sustainability Transitions at DRIFT, Erasmus University of Rotterdam

Mr. A. A. Eftekhari,

PhD Researcher at TU Delft

Mr. B. Kapper,

Regisseur Energie, Water en Kust, Natuur en Milieu Federatie Zuid-Holland

Questions:

1) Please score each barrier/uncertainty according to the relative importance for the short-term full scale deployment of CCS (up to 2020).
2) Please score each barrier/ uncertainty according to the relative importance for the medium-term full scale deployment of CCS (2020-2030).
3) Please score each barrier/ uncertainty according to the relative importance for the long-term full scale deployment of CCS (2030-beyond).
4) Please indicate any barriers/ uncertainties which are not included but are important to overcome for the full scale deployment of CCS.
5) What are the effects of these barriers/ uncertainties to be expected in the short-term, medium-term and long-term scenarios respectively.
6) How can the most important factors be overcome?
7) Please rank the three scenarios according to their feasibility.
8) Are the barriers of the same importance in different locations globally?
9) In the case of Port of Rotterdam what would be the ideal mitigation mix strategy to ensure growth and economic development?
10) Do you find the goals set by RCI realistic or ambitious?
11) Is it the government/municipality or the business sector who must take the lead for the full-scale deployment of CCS?
12) What is the perceived need for CCS in Rotterdam?
13) Is Port of Rotterdam going to become Europe's hub for CO_2? And what is the role of CCS in this?